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THE HIGH-LIFT WING. REMARKS ON THE PREDICTION OF CHARACTERISTICS

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ABSTRACT. Examination of some problems encountered in predicting the characteristics of high lift wings with or without additional high lift devices. Compromises must be made between the qualities desired at high speeds and those desired at takeoff speeds. Attention is given to existing means of controlling lift or distributing the load on a wing by detachment. Particular emphasis is placed on the processes of prediction of maximum lift coefficient and its increase by means of high-lift devices; these are compared for the case of a moderately long and moderately swept-back wing equipped with conventional high lift devices. It is considered that improvement in prediction is related to a better understanding of detachment phenomena. Results of current studies are briefly reviewed, and various procedures to increase lift by blowing are described. A71-27476. /3*

1. INTRODUCTION

In this report, we shall present several problems which presently confront the engineer who wishes to predict the characteristics of a high-lift wing, whether or not it is fitted with high-lift devices.

These various problems have been known for a long time, and there are numerous solutions for simple cases. Now, however, wings can be equipped with more and more varied and more and more complex devices to meet the greater requirements — notably, the compromise between high speed and low take-off speed.

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*Numbers in the margin indicate pagination in the original foreign text.

It thus seems interesting to make a new examination of lift problems, and to review existing methods either for examining the lift, or for evaluating the load distribution on a wing with detachment, or more completely, the value of the maximum lift coefficient $C_{z\ max}$.

More particularly, we shall stress the prediction of $C_{z\ max}$ and the gain in C_z with a high-lift device. These procedures will be compared for the case of a moderately long and moderately swept wing (of the Airbus type, for instance) fitted with classical high-lift devices.

It is probable that improvement in predictions will result from a better understanding of the detachment phenomena. Thus we shall review the work in progress, and results which we have obtained up to the present.

Various high-lift techniques by blowing are described in two large categories: "direct" blowing (by fan or by engine exhaust), and by "indirect" blowing (by diverting air around the engine). Their characteristics are presented, and their "tendencies" observed.

II. NOTATION

/4

- b Half-span of a wing or of flaps
- c Chord of flap or camber
- ΔC_z Coefficient of lift due to flaps
- $\Delta C_{z\ j}$ Coefficient of lift due to jet momentum
- $\Delta C_{z\ \Gamma}$ Coefficient of lift due to hypercirculation

$$C_\mu = \frac{\dot{m}_j V_j}{qS}, \qquad C_{\mu\infty} = \frac{\dot{m}_\infty V_\infty}{qS}$$ Blowing coefficient

- d Width of blowing slot
- e Relative thickness of a profile

F Thrust

h Height above ground

$H = \frac{\delta^*}{\theta}$ Form factor

l Chord of a profile

$\dot{m}_j$ Mass flow rate of engines (or diverted around the engines)

$\dot{m}_\infty$ Inlet mass flow rate

S Reference surface

S_p Surface of wing panel affected by blowing

V_j Velocity of blowing jet

V_∞ Velocity infinitely upstream

T Engine thrust at cruising

X Drag

Z Lift

δ Angle of flap setting

δ_j Angle of jet with axis of aircraft

δ^* Displacement thickness

ε Wing taper or deflection

$\eta = \frac{F}{T}$ Jet efficiency after rotation /5

θ Momentum density

λ Length

σ_c Position of maximum camber

σ_e Position of maximum thickness

Subscripts

g Refers to total blowing ($C_{\mu_g} = C_{\mu_n} + C_{\mu_v}$)

n Refers to the leading edge

v Refers to the trailing-edge flap

R Refers to re-attachment

III. METHODS FOR PREDICTION /6

3.1. General Discussion

In this chapter we shall predict the characteristics of a high-lift wing: this will be limited, however, to prediction of $C_{z\,max}$ and of ΔC_z produced by a high-lift device.

For preliminary-design calculations, a knowledge of $\left.\frac{\partial C_z}{\partial i}\right|$ in the linear domain, and the value of $C_{z\,max}$ are generally sufficient. They can be furnished by empirical methods, for example. Here we shall cite certain of these methods, and shall give some results in Chapter IV.

For a more advanced design, evaluation of C_z near the maximum lift is needed, as well as the load distribution over the span. We shall present some methods used up to the present time. It is probable that improvement of these methods will require a better knowledge of the "cartography" of detachment from the wing surface. As far as we are aware, this type of study is still only beginning. We shall thus give only a few brief indications of detachment configurations and of studies which have been undertaken on this subject.

3.2. Present State of Predicting Characteristics

3.2.1. Introduction

It is known that it is possible to predict the aerodynamic characteristics of obstacles in a potential flow, even for complicated obstacles, due to computers which are now available. Prediction is difficult, on the other hand, for flow which is partially or completely detached, even with modern computational methods.

Whatever the regime (detached or not), the engineer must predict, within /7
a certain margin of error, several characteristics essential to a preliminary

design with minimal computation. In this section, we shall cite the methods used currently; in Section 3.4 we shall discuss the phenomena of detachment.

3.2.2. "Non-Detached" Domain

We should recall that values of the slopes $\partial C_z/\partial i$ and of the gains ΔC_z due to flaps can be obtained relatively easily by the classic methods of Lowry and Polhamus [25], J. De Young [27], etc. On comparing these results with those of more elaborate methods (the rheo-electric cell, for example), it is found that they are quite sufficient for preliminary work.

3.2.3. "Partial-Detachment" Domain

A comparison of predictions of $\partial C_z/\partial i$, ΔC_z (δ_v), and $C_{z\ max}|$ by classic methods — Bore and Boyd [30] and A. D. Young [28] — is given in Chapter IV. We note that the classic methods lead to results acceptable for preliminary design for wings of moderate aspect ratio and moderate sweep-back, and also for relatively simple trailing-edge flaps. To our knowledge at least, predictive methods for high-lift devices at the leading edge, especially for flaps, would give results which are open to criticism.

3.2.4. Prediction for High Lift Devices Using Blowing

Examples of high lift by blowing will be presented in Chapter V. We shall note here the work on "indirect" blowing (or "internal" blowing) by Poisson-Quinton [1] and Williams [4], among others. This work makes it possible to predict values of ΔC_z due to trailing-edge flaps over a large domain of aspect ratio and sweep of the wing. In contrast, we do not have a method of predicting the characteristics due to leading-edge blowing.

As for "direct" blowing (the engine jet blowing directly on a flap), research to date has not led to the development of a predictive method. We shall, however, present in Chapter V a very rudimentary method based on /8 experimental results which we have available at present.

3.3. Effect of Some Parameters

3.3.1. Reynolds Number

While the aerodynamic characteristics depend above all on the geometry of the obstacle, it is nevertheless known that the effect of the flow is manifested mainly through the Reynolds number, and to a lesser degree (at low velocities) through the Mach number. We shall also indicate the change of aerodynamic characteristics near the ground.

Plates 1 and 1a present values of $C_{z\ max}$ *vs*. R according to McRae. On the one hand, there is a large dispersion in the results; on the other hand, there are variations of very different nature for certain configurations. It is also known that each family of profiles leads to a well-defined variation, and that it is not easy to propose a simple and general method. We note that there are roughly two domains: $R < 10^6$ and $R > 10^7$ in which the values of $C_{z\ max}$ are relatively constant. To the extent possible, it would be interesting to use the characteristics measured at $R > 10^7$, the Reynolds number order for an aircraft in the regime where detachment occurs or is close to detachment conditions.

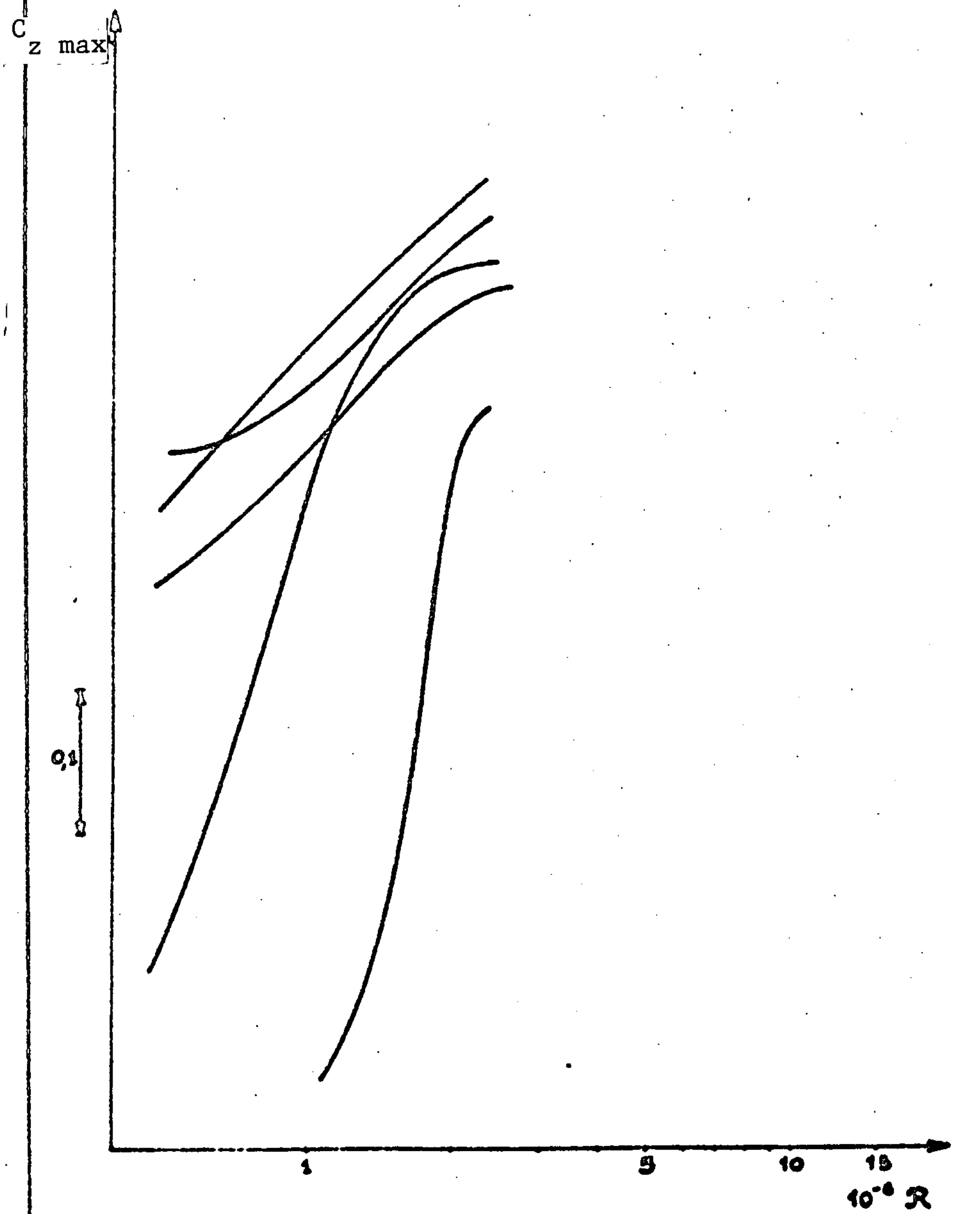
3.3.2. Mach Number

At low velocities ($M < 0.3$), compressibility phenomena can appear locally at high angles of attack. This does not seem to have been the subject of published papers, although one can see some overall tendencies in Plate 2, from McRae and Bore.

3.3.3. Ground Effect (Plate 3) /9

The presence of the ground is known to produce an increase in lift. It is less well known that it can equally produce a decrease in $C_{z\ max}$ (Gratzer [33]),

Plate 1. Effect of Reynolds Number



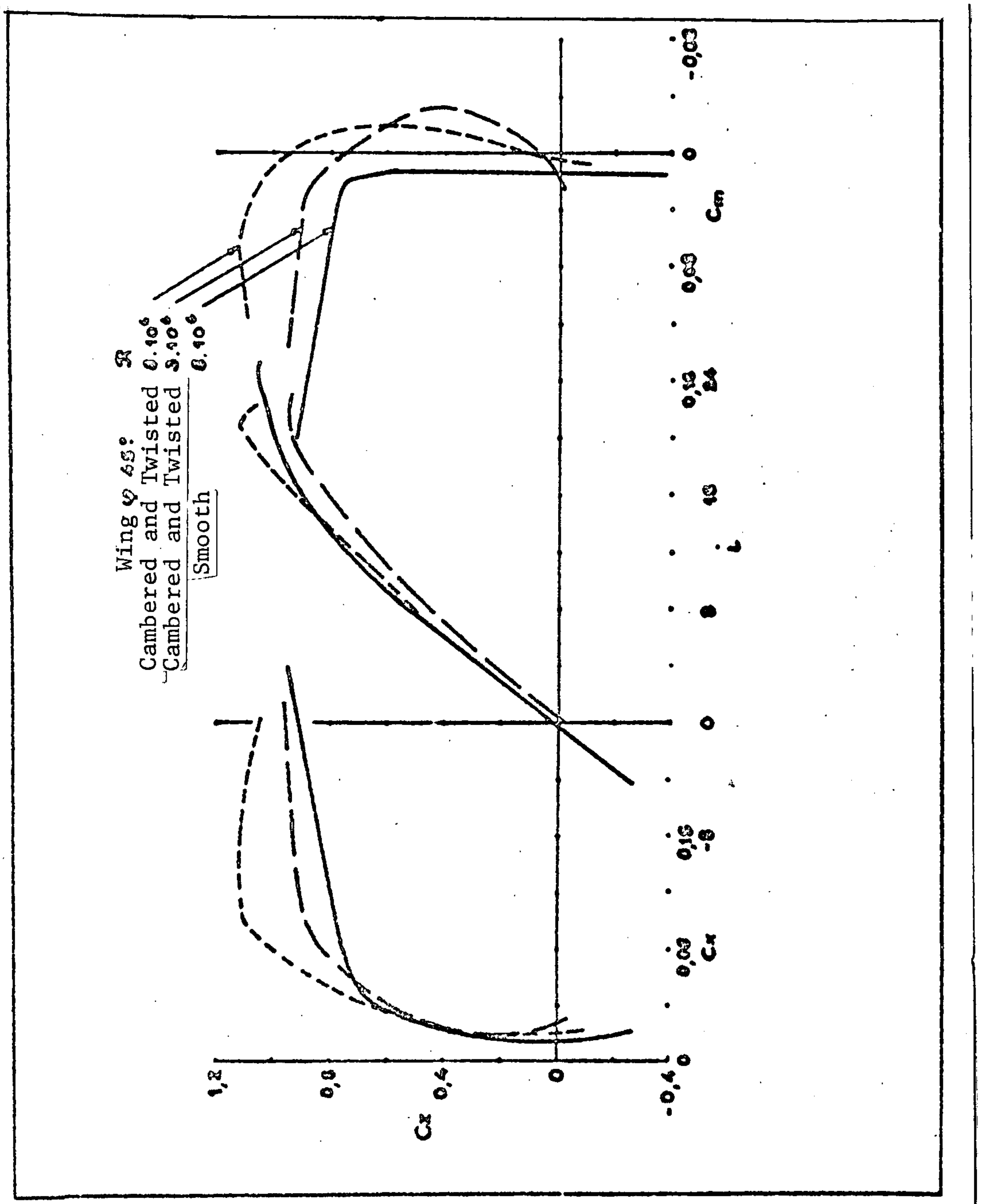


Plate 1a. Prediction of Characteristics.
Modified wing - Effect of R.

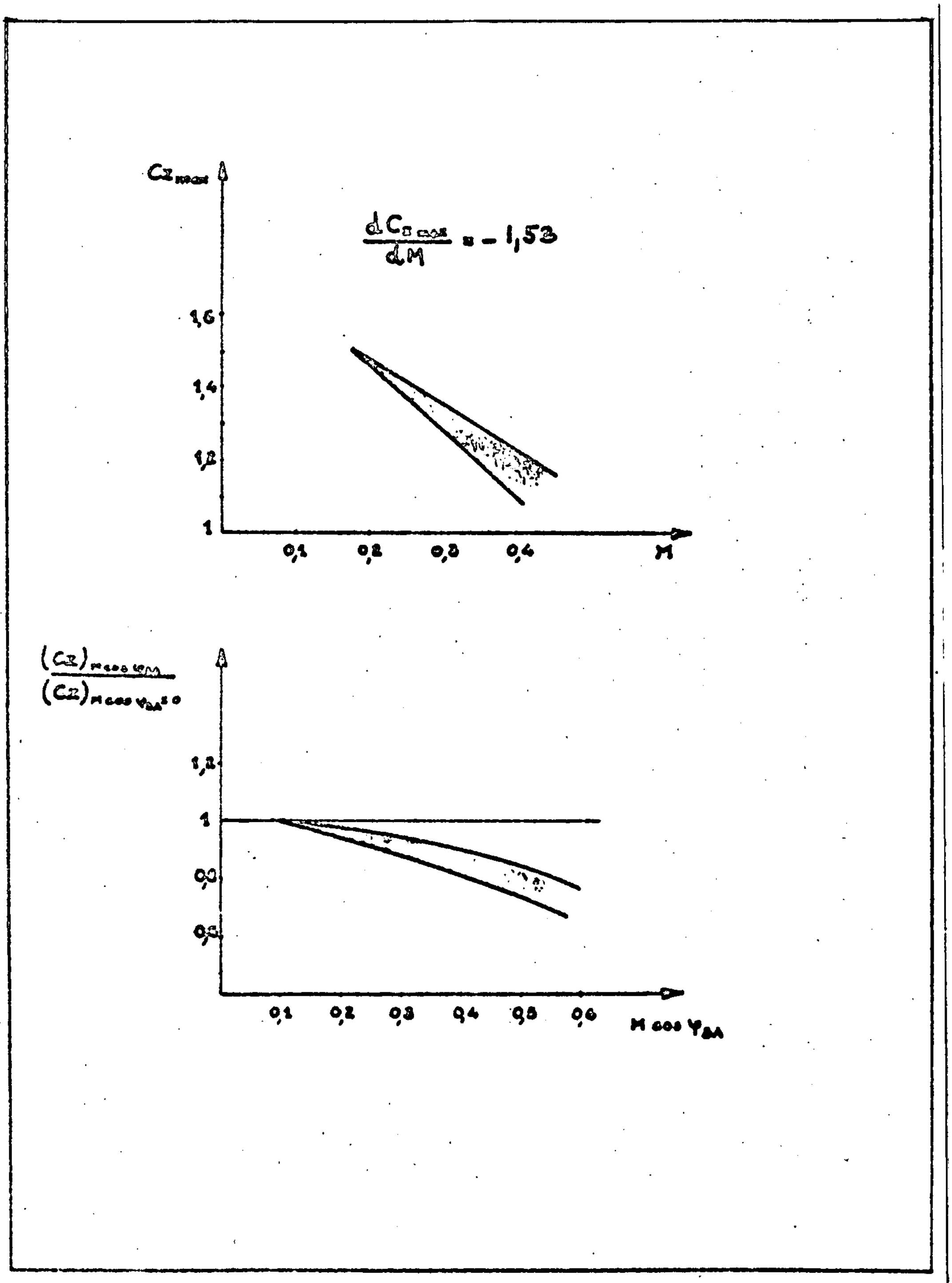


Plate 2. Effect of Mach Number

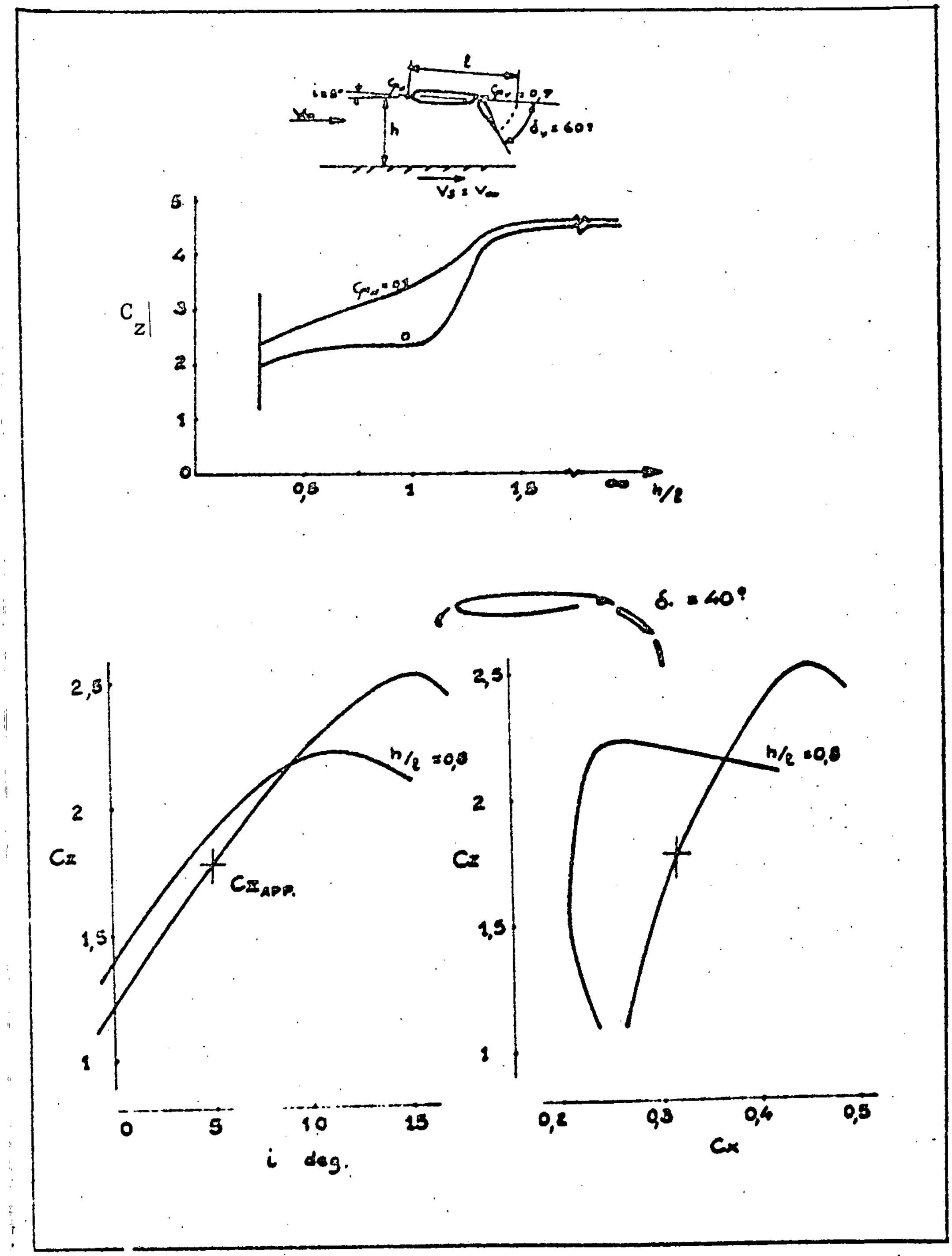


Plate 3. Ground Effect.

which can neutralize the increase indicated above.

In the case of internal blowing, Gersten [5] has shown that there is a threshold below which the presence of the ground changes the value of $C_{z\ max}$. This level is the same as in the absence of leading-edge blowing, but the decrease on the low side is less abrupt.

3.4. Detachment: Definitions and Description

In the strictest sense, there is no flow without detachment, yet there are regimes which differ more or less widely from the potential regime.

- The regime with a slipstream. This regime differs little from potential flow when there is a slipstream from the after point of a profile; obviously, it is completely different with a slipstream at the forward part of a plate. This last problem has been treated by many authors (Peres, Levi-Civita, Villat) for about thirty years without invoking the idea of a viscous fluid, and by using equivalent potential flow models.

- The turbulent regime. This is a case of classic turbulent detachment: vortices at the edges and at the apex. As above, these calculations can be effected by replacing the real flow by a potential-flow model; the complexity of the calculations and the value of the result of course depend on the model chosen.

- The regime of partial detachment. This regime is especially important, /10 since it conditions the flow over high-lift wings. It is characterized by the presence of "bubbles" of detachment whose presence modifies the shape of the $C_z(i)$ curve, among other things. It appears that no attempts have been made to calculate flow with detachment "bubbles" using an equivalent-potential method.

In three-dimensional flow, the flow is characterized by detachment lines and re-attachment (Horton, [16]). There seems to be a relationship between the three-dimensional detachment bubbles and the marginal and apical vortices: it can be assumed, for example, that the detachment bubble at a leading edge corresponds to the apical "cornet" vortex of a strongly swept wing.

The following Plates show several configurations with detachment.

- Plate 4 (from Solignac, [31]) gives several current problems in detachment.
- Plate 5 (from Solignac, [31]) gives several types of flow detached from a smooth profile.
- Plate 6 (from Horton, [16]) gives flow with a slipstream on a profile with leading and trailing-edge flaps.
- Plate 7 (from Horton, [16]) gives flow with detachment for a three-dimensional wing.

3.5. Two-Dimensional Problem; Criteria for Detachment /11

3.5.1. Preliminary Remarks

The "quantitative" study of a flow with detachment must be able to yield the pressure distribution over the surface of the obstacle; more schematically, it is a matter of knowing the beginning (detachment criterion) and end of detachment. Furthermore, since the pressure can be assumed to be constant in the interior of the detached flow, it only remains to evaluate this pressure. Finally, if one wishes to determine the complete flow field, it is necessary to know the angle of the boundary streamline with the surface of the obstacle. In the following, we shall cite results which we have available at the present time, chiefly for the two-dimensional problem.

3.5.2. Geometric Criteria

Criteria for the existence of leading-edge detachment on a profile have been proposed by Ville and Wanner [10]:

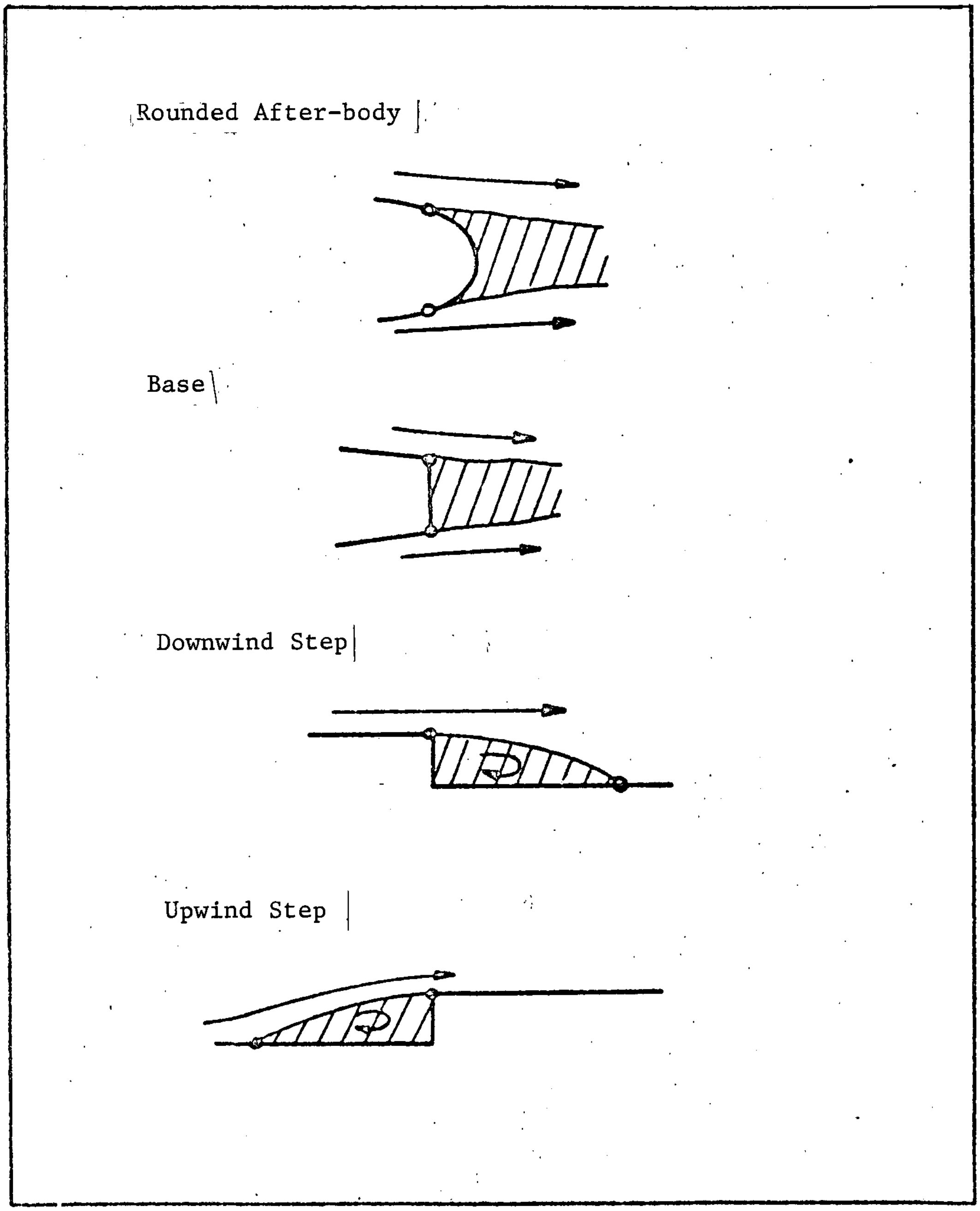


Plate 4. Detachment. Types of problem studied.

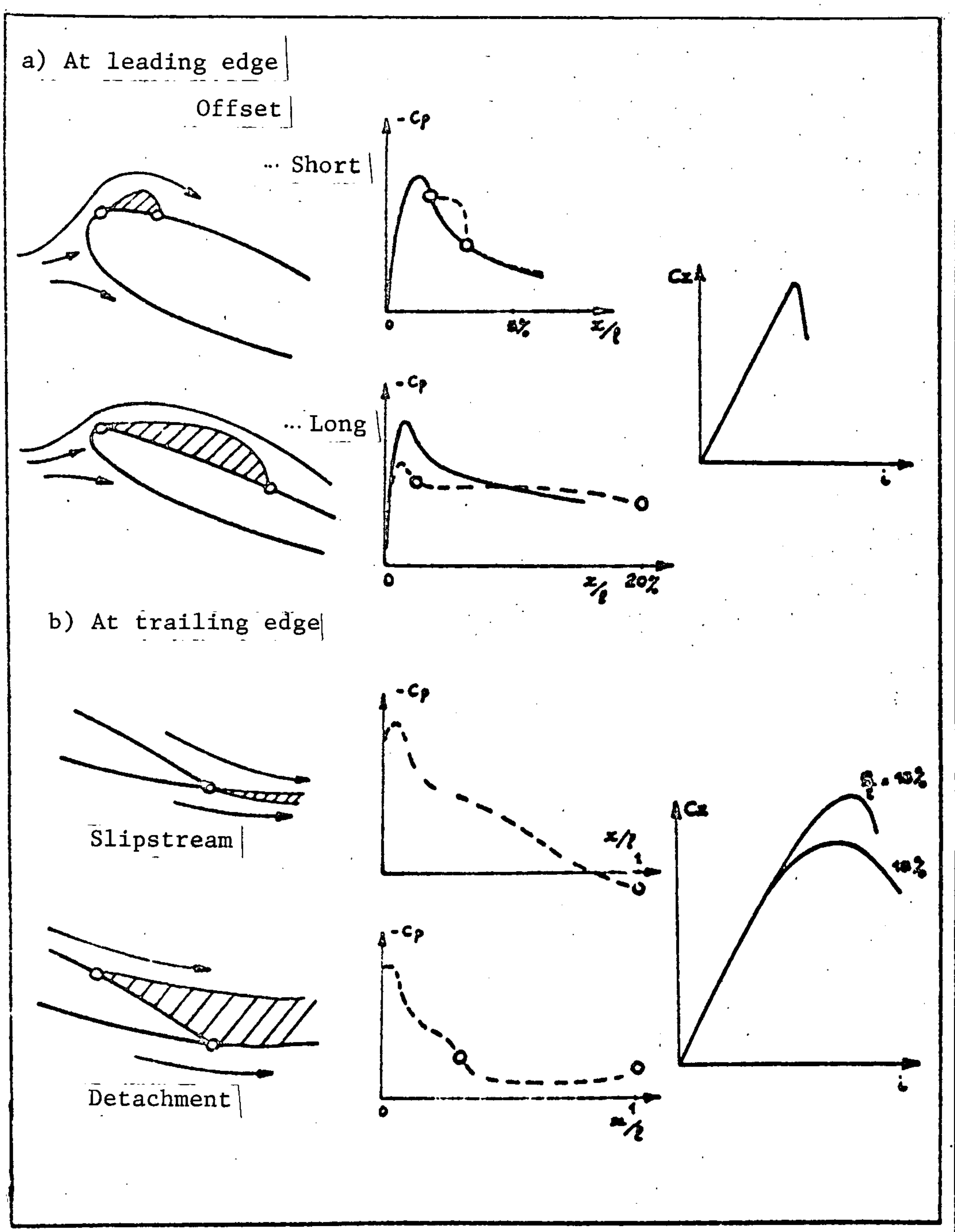


Plate 5. Detachment on a profile.

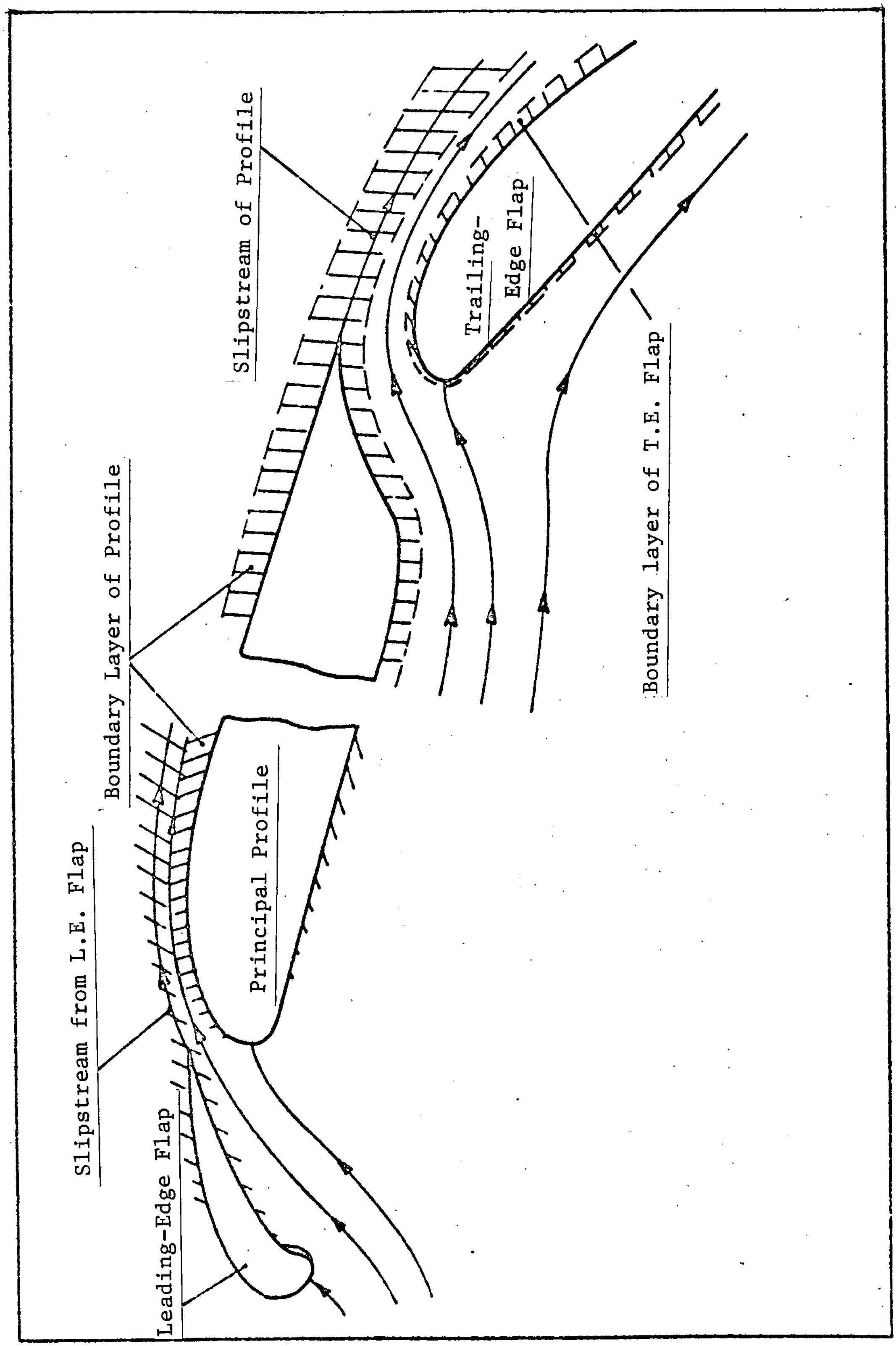


Plate 6. Boundary layer and slipstream on a wing with high-lift device.

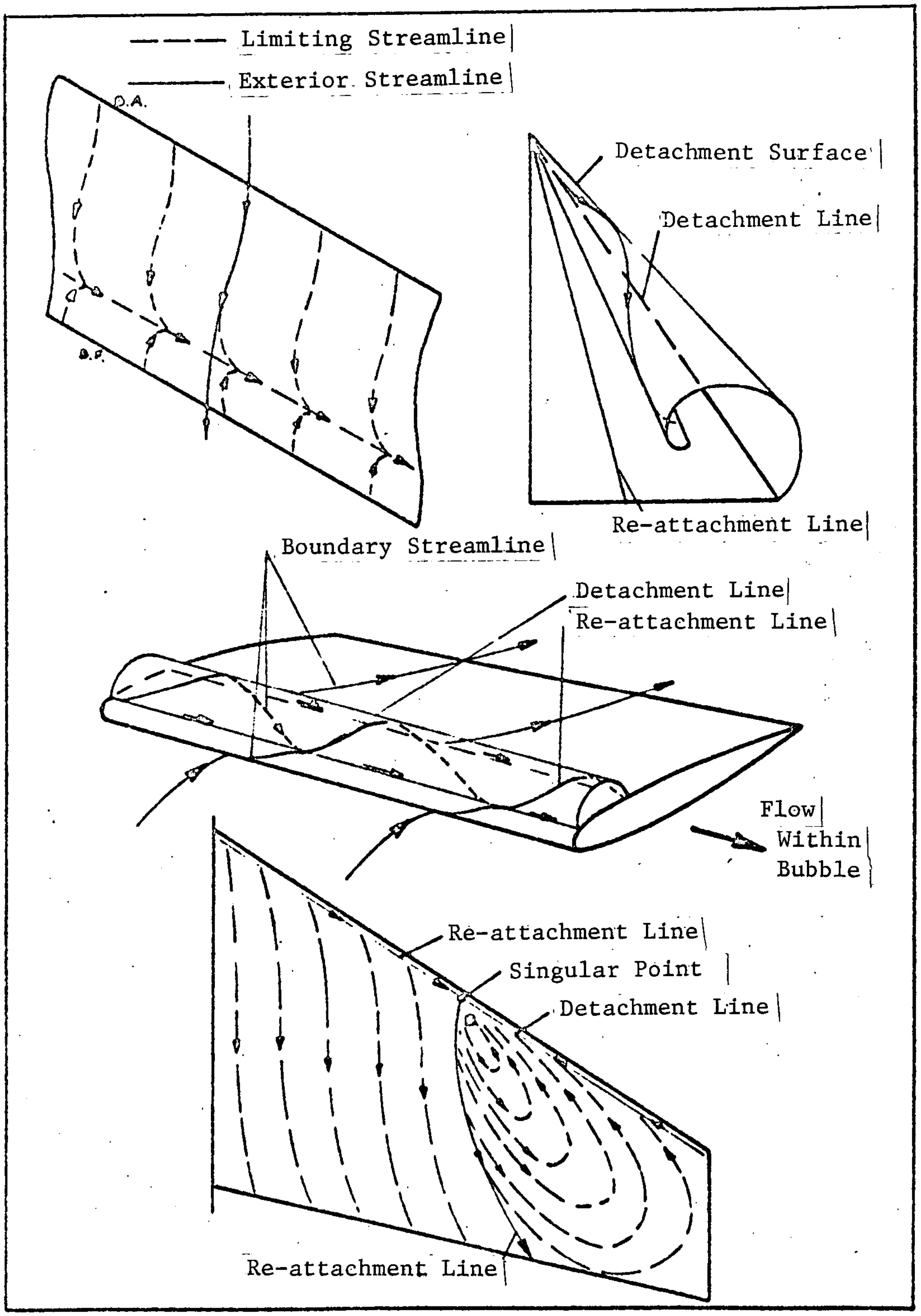


Plate 7. Detachment configurations.

$R \cdot \bar{r} < 3 \cdot 10^4$ for laminar detachment;

$R \cdot \bar{r} > 3 \cdot 10^4$ for turbulent detachment;

with $\mathcal{R} = \frac{V_\infty l}{\nu}$ and $\bar{r} = r \sqrt{1 + \frac{\sigma_c^2}{10^3 \; r \cdot e}}$

r is the reduced radius of the leading edge,

$\bar{r}$ is the reduced mean radius of curvature in the region of the leading edge.

3.5.3. Distribution Criteria

Knowledge of the velocity or pressure distribution will allow localization of detachment to a certain extent. Critical values of K_p or of V have been proposed by certain authors. This procedure, which is very simple, allows one to obtain at least an idea of the possibility of detachment at a given point.

A more precise criterion is given by Stratford [12] for turbulent flow: /12

$$K_p \left[x \frac{d K_p}{dx} \right]^{1/2} = 0{,}39 \left(10^{-6} \mathcal{R} \right)^{1/10}$$

This criterion takes into consideration the distribution of K_p and its gradient.

3.5.4. Criteria for Momentum Thickness and for Form Factor H

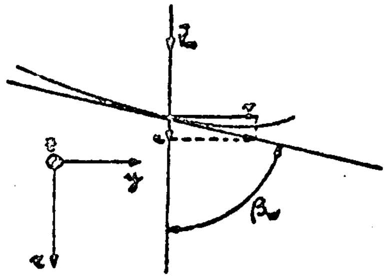
Some criteria have already been presented. Ville has given some at the 4th Conference on Aerodynamics [9]; Solignac [31] has given others.

Ville's criterion permits localization of leading-edge detachment, and shows the nature of the detachments (long or short bubbles, etc.). A correlation by Gaster has also been presented by Solignac [31].

With regard to the form factor H [31], the detachment will be stable for H > 3.

3.5.5. Criteria for Three-Dimensional Detachment

Maskell (see Horton, [16]) considered a "boundary" streamline at the wall and in the boundary layer (thus different in general from the streamline outside the boundary layer). Its slope is defined by

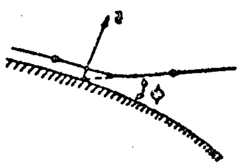


$$tg\,\beta_w = \lim_{z \to 0} \frac{v}{u} = \frac{\left(\mu \frac{\partial v}{\partial z}\right)_w}{\left(\mu \frac{\partial u}{\partial z}\right)_w}$$

The detachment line corresponds to $t_g\ \beta_w = \infty$. Plate 7 gives an example of detachment for a wing with infinite side-slip. /13

3.5.6. Detachment Angle

For two-dimensional laminar flow, with x known, the direction of a streamline in the z-plane is given by the formula of Oswatitsch (see Horton, [16]):



$$tg\,\phi = -3\,\frac{\partial \tau_w/\partial x}{\partial p/\partial x}$$

$\tau_w = \mu\left(\frac{\partial u}{\partial z}\right)_w$ begin the parietal stress.

3.5.7. Partial Conclusions

From this brief sketch, it would appear that the criteria mentioned allow at least a qualitative interpretation of the detachment phenomena on a profile. At the present time, it is possible to determine the position and conditions of bursting for leading-edge bubbles. It would, however, be interesting to determine the pressure within a bubble, its length, and eventually, the boundary layer conditions at the point of re-attachment.

The preceding results can probably be transferred to the case of a wing (within a certain range of sweep and aspect ratio, and sufficiently far from the tips). For strongly swept wings, however, a three-dimensional boundary-layer calculation would be necessary, when the detachment criterion of § 3.5.5. could be used.

Thus, it can be stated that at present we are far from an immediate prediction for preliminary design work. Although it is a difficult research field, it can be expected that study of the wing with detachment can provide at least qualitative criteria for the choice of geometric parameters at the design stage.

3.6. Three-Dimensional Problem /14

3.6.1. Preliminary Remarks

For a long time, profiles have been tested in wind tunnels (tests between panels, or tests on a straight wing with aspect ratio greater than 5). Furthermore, it can be established (§ 4.2.2.) that prediction of the profile characteristics C_z (i) and $C_{z\ max}$ gives acceptable values. The question thus arises: can the results obtained in the two-dimensional case be used for three-dimensional prediction? In the following, we shall cite several methods using two-dimensional results, and other more complex methods which permit direct calculation of the whole wing.

We first note that obtaining the highest possible value of $C_{z\ max}$ is a necessary condition, but not a sufficient one. It is also necessary to ensure correct separation: progressive separation in the longitudinal plane. It is thus important to know not only the C_z (i) curve near $C_{z\ max}$, but also the load distribution (or the local C_z) along the span. We shall present below a few calculation methods, and some results obtained.

3.6.2. Presentation of Methods (Plate 8)

Tapered Wing

The problem of the tapered wing has been treated for a long time by many authors, including Legendre [37] and Mangler [38]. The results differ according to the vortex model considered. It is possible to use a very short ($\lambda < 1$) rectangular wing, for example, as the "lifting element" in calculations for a wing of greater aspect ratio.

Straight Wing /15

One of the best-known computational methods is that of Peres, Malavard, and Romani [17], which has been discussed by Chaffois [18] and used by Sabathe and Condaminas [11]. The method consists chiefly of the use of a constant slope $\frac{\partial C_z}{\partial i}$ for each profile (slope of a "fictive profile"). The local load-distribution law is then obtained by determining through successive approximations the law of increase for these "fictitious slopes."

Swept Wings

The same method of fictitious slopes has been applied to a swept wing by Dumez [19], starting from the method of Weissinger, and by Harper and Maki [13]; the latter used the aerodynamic characteristics of profiles placed perpendicular to the 25% line. We shall give some results of calculations by this latter method in § 3.6.3.

In the case of a wing with aspect ratio greater than 4, Axelson and Haacker used an especially simple vortex model obtained by the method of Weinig (applicable to a rectangular wing, $\lambda \sim 0.25$, with detachment) by replacing the half-wing by a short rectangular wing, and then including the sideslip of the fictitious wing.

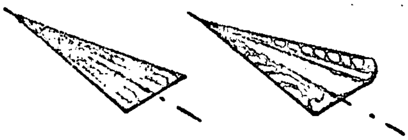
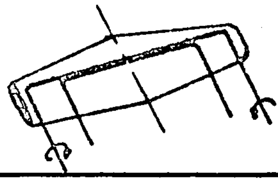
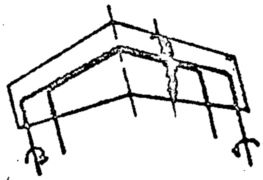
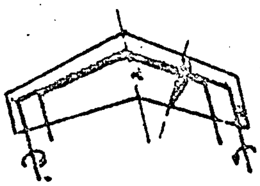
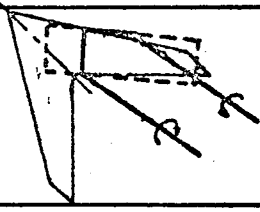
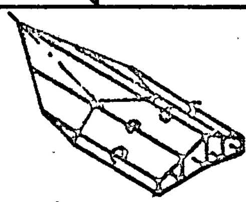
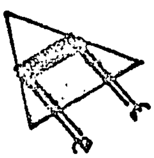
Region	Author	Model	Observations
$\lambda < 2$	Legendre Mangler		$C_z < C_{z\,max}$ C_z (i) nonlinear Wings without high-lift devices
$\lambda > 4$ $\phi \sim 0$	Peres		Wing with high-lift device C_z (i) beyond critical point
$\lambda > 2$ $\phi \neq 0$	Dumez		Profile parallel to V Wing with high-lift device C_z (i) beyond critical point
$\lambda > 2$ $\phi \neq 0$	Harper Maki		Profile perpendicular to the 25% line Weissinger's method of calculation Wing with high-lift device
$\lambda > 4$ $\phi \neq 0$	Axelson		Wing without high-lift device Single-vortex model Study of super-critical region
λ and ϕ arbitrary	Gersten		Smooth wing Super-critical region
λ and ϕ arbitrary	Sacks		Wing smooth and without indentation Super-critical region

Plate 8. Methods of calculation.

It appears that in this method (at least for the sweep and angle of attack considered) the shape of the profile is not critical. /16

The decomposition of a wing into lifting elements has been used by various authors, especially by Gersten [5] (lifting elements of short aspect ratio in the direction of the velocity) and by Sacks [20] (lifting elements of great aspect ratio perpendicular to the velocity). In these methods the detachment is represented by the departure of vortex lines from the surface of the wing, the departure angle being fixed in advance (Gersten) or obtained by iteration (Sacks).

In conclusion, mention should be made of the method of Taganov [26], in which the detachment model (vortices at apex and at tips) is made up of doublets.

3.6.3. Results

First-Critical-Section Method

In Plates 9 and 10, one may compare the distribution over the span of the operating lift coefficients C_{zl} with the distribution of $C_{zl\ max}$. It is seen that the critical point (end of the linear portion of the lift curve) is reached when the two curves coalesce; furthermore, the corresponding section is the first section detached. If one wishes to obtain detachment as close as possible to the wing root, by means of either a leading-edge slot (Plate 9), or by means of a spoiler (Plate 10), it can be seen that the method can at least serve as a guide in the choice of a configuration.

The method must give an indication on C_z (C_x) of the point of abrupt increase of C_x, or on C_m (C_z) of a large variation in the momentum. Plates 11 and 12 show that the method leads to an acceptable prediction (less than 20% in C_z), which is generally pessimistic. /17

Prediction of Characteristics

Critical-Section Method

Leading-Edge Slot

From [13]

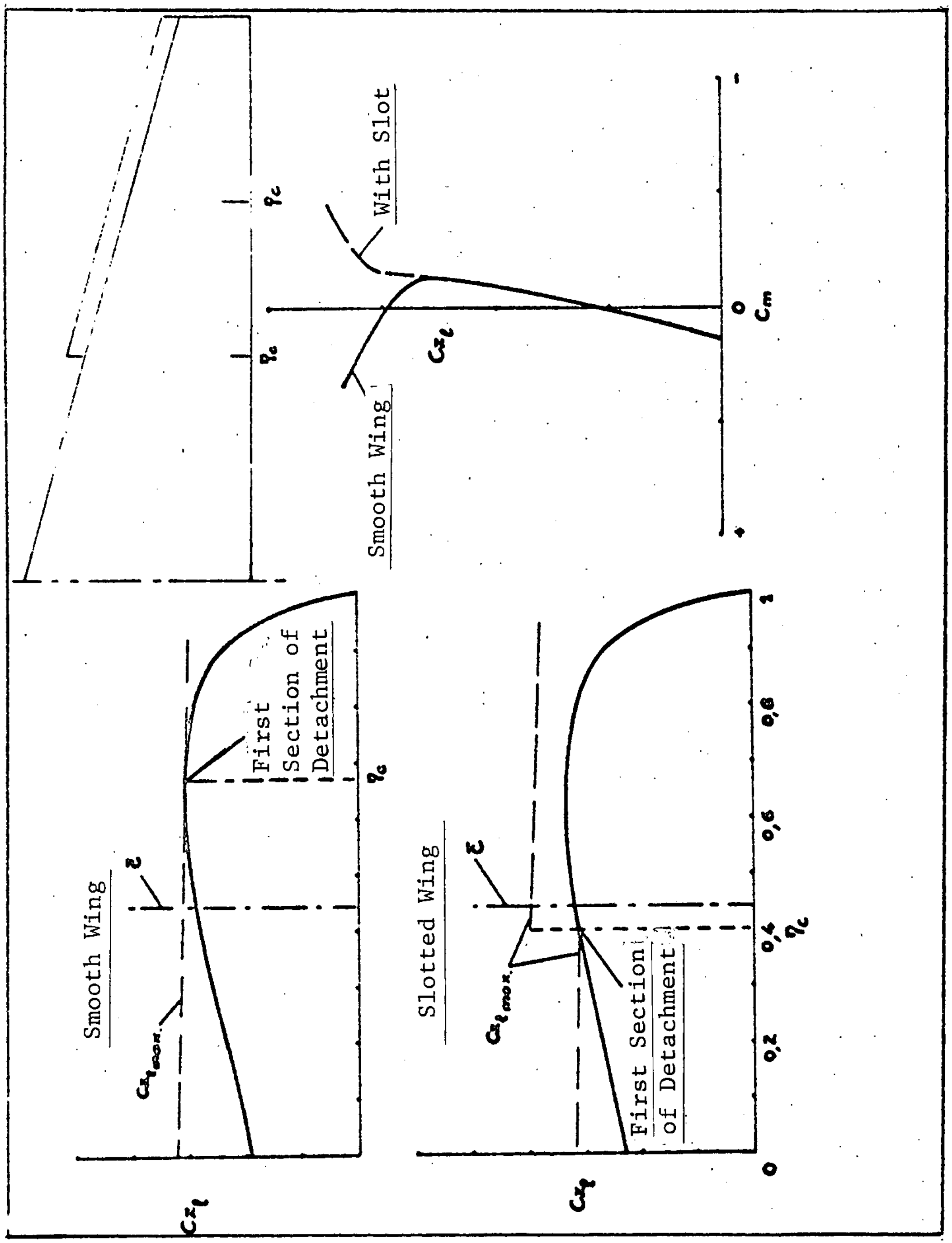


Plate 9

Prediction of Characteristics

Critical-Section Method

Detachment Spoiler

From [13]

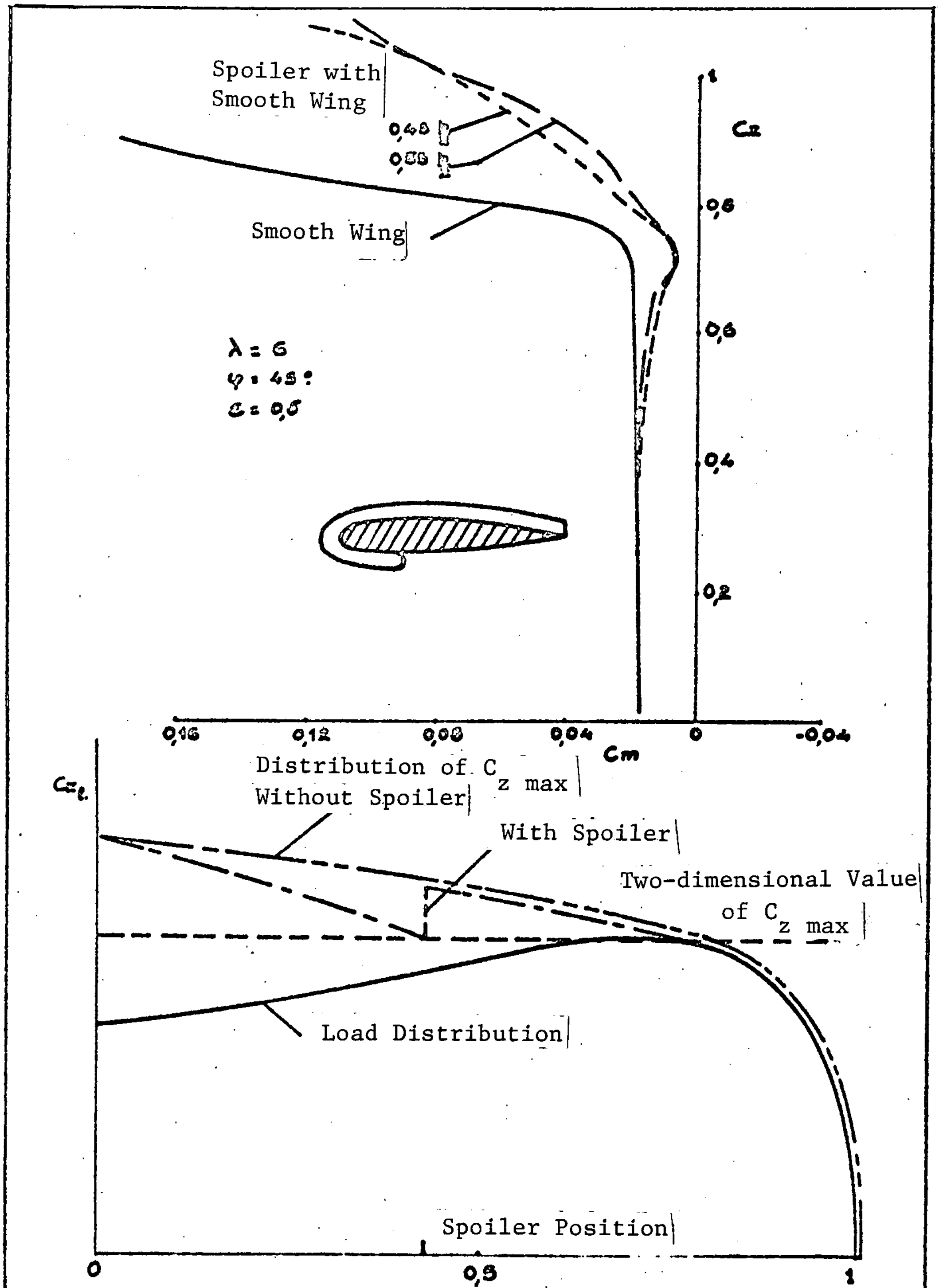


Plate 10

Prediction of Characteristics

Critical-Section Method

Prediction for various λ and φ — Smooth wing

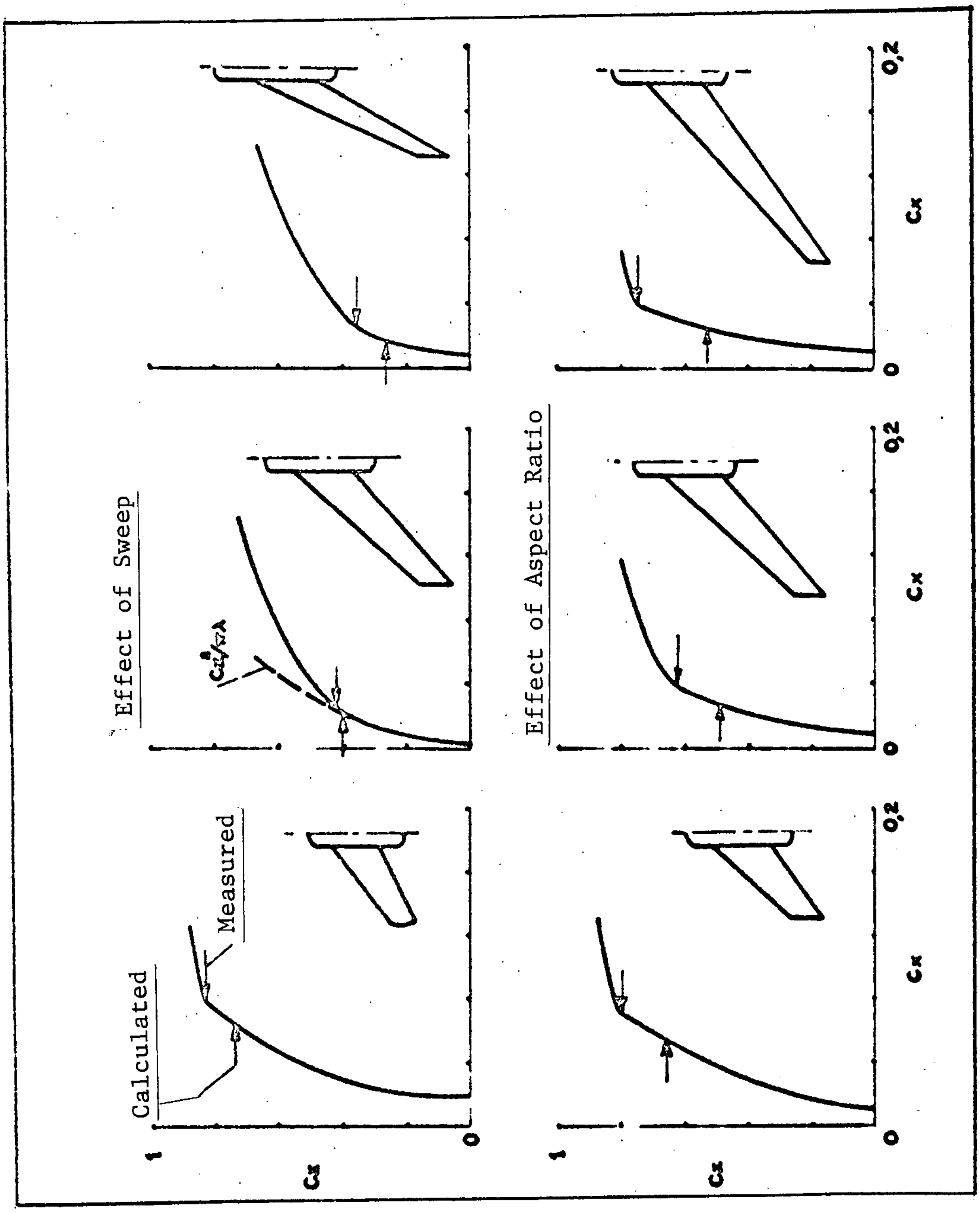


Plate 11

Prediction of Characteristics

Critical-Section Method

Prediction for Modified Wings

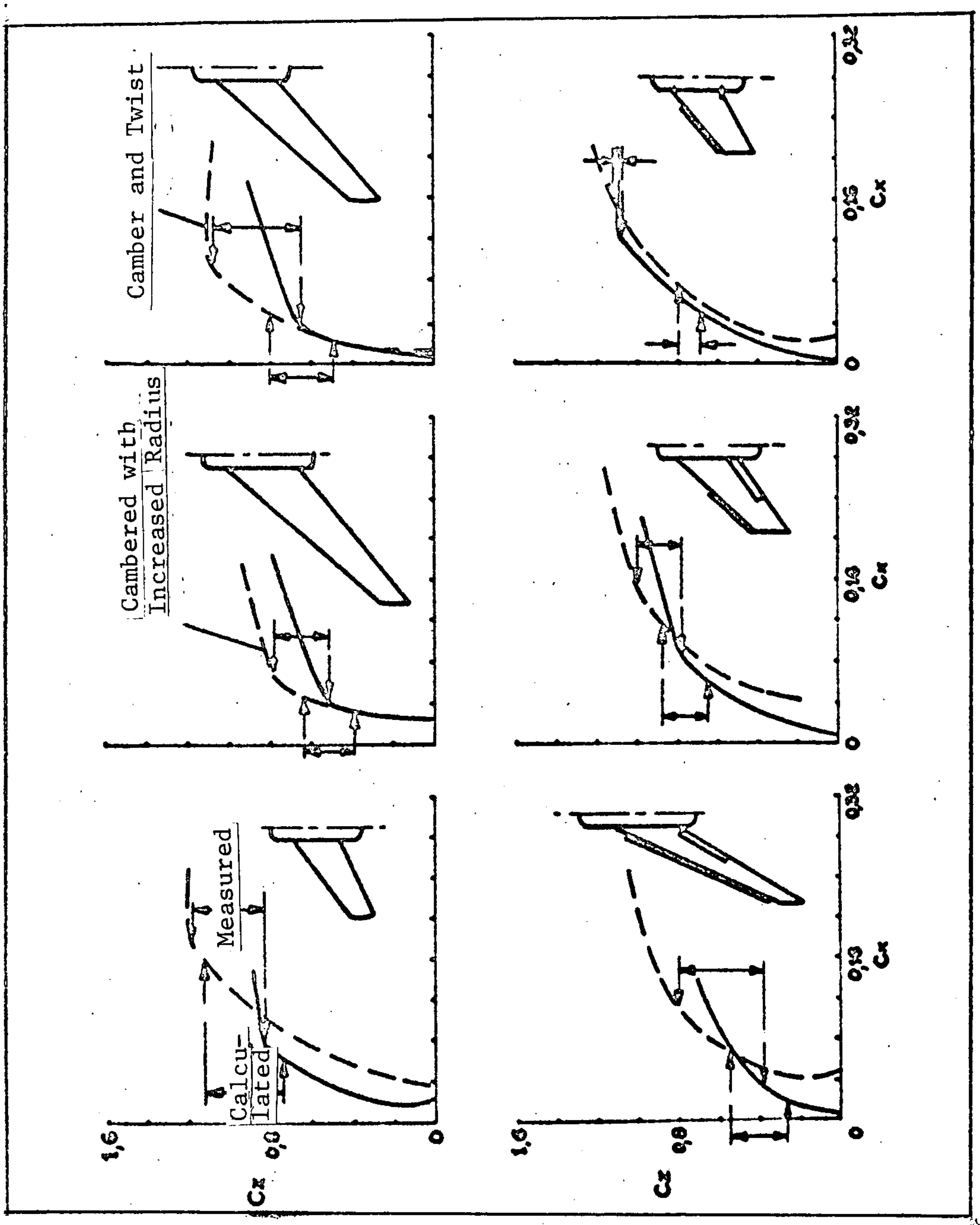


Plate 12

Comparisons of Two- and Three-Dimensional Results

Harper and Maki [13] compared experimental C_z (i) curves for several wing profiles with "two-dimensional" curves (the slopes were always calculated by Weissinger's method). Plates 13 and 14 show that the "two dimensional" values of the maxima are generally far below the experimental curves; this is particularly true at the side of the wing root. In this way, one can explain the fact that the first-critical-section prediction generally gives a result smaller than reality. The maximum difference at the side of the wing root can be explained by a "natural stabilization" of the boundary layer in this region. Furthermore, this stabilization can cause difficulties in the localization of detachment by several methods (slot, spoiler, etc.), since detachment can be more difficult near the wing root.

As for the pressure distribution — more exactly, the distribution of K_p/C_{zl} — near $C_{z\ max}$, Plate 15 (from Harper and Maki) shows that the experimental and calculated curves are quite close, except near the wing root.

Axelson's Method [14]

Plate 16 gives a comparison of the distributions over the span, as well as curves of C_{z_i} (i) at angles of attack greater than 20° and for a wing with $\phi = 45°$. It is remarkable that Axelson's relatively simple vortex model could give such good agreement with experiment.

3.6.4. Partial Conclusions /18

Although it is well known, it must be emphasized that obtaining a large theoretical value of $C_{z\ max}$ is not essential. What is absolutely necessary is obtaining the largest value of C_z which can be used: at least, without an abrupt variation in the pitching-moment curve (detachment localization at the

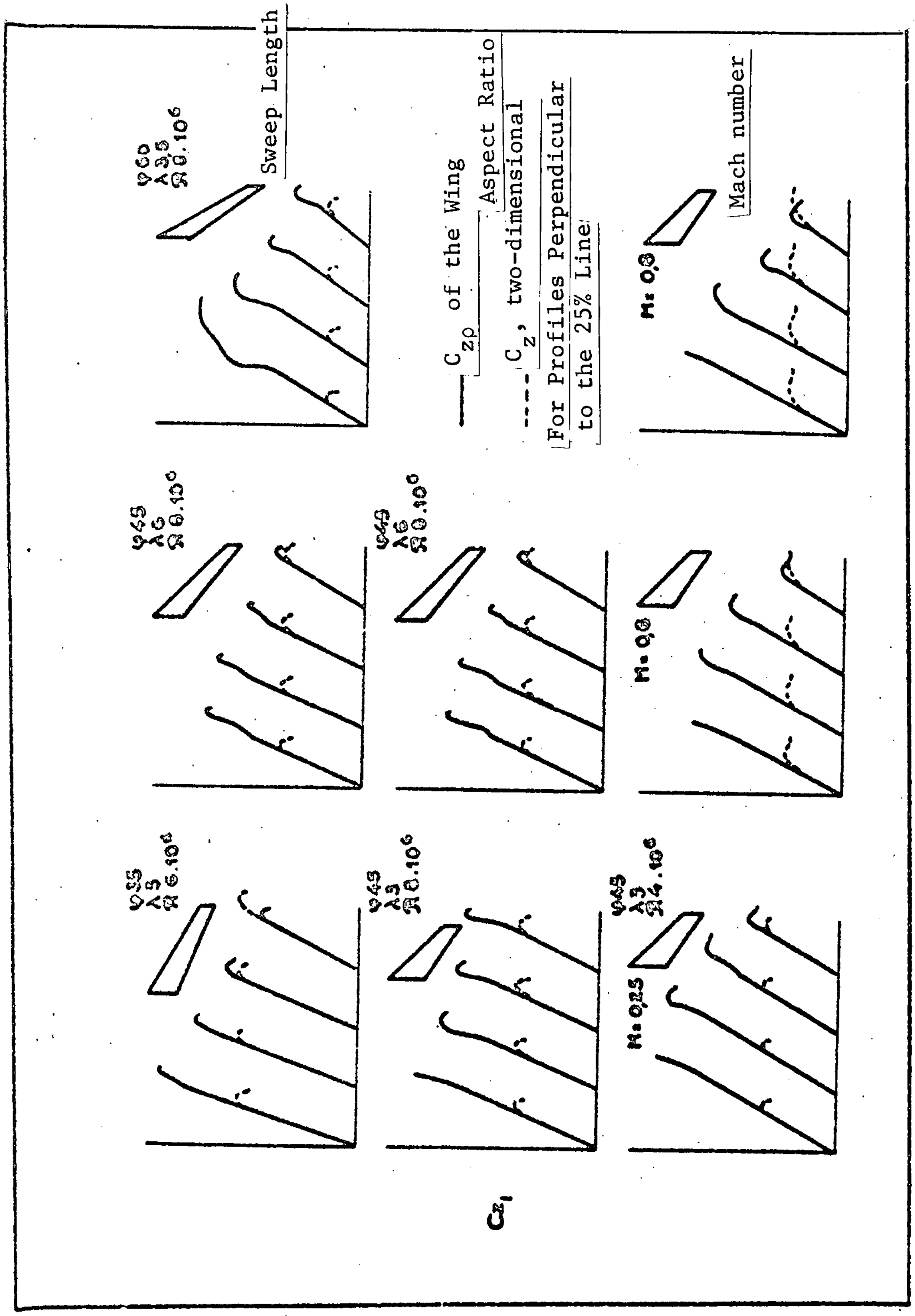


Plate 13. Comparison of experimental two- and three-dimensional C_z (i) curves.

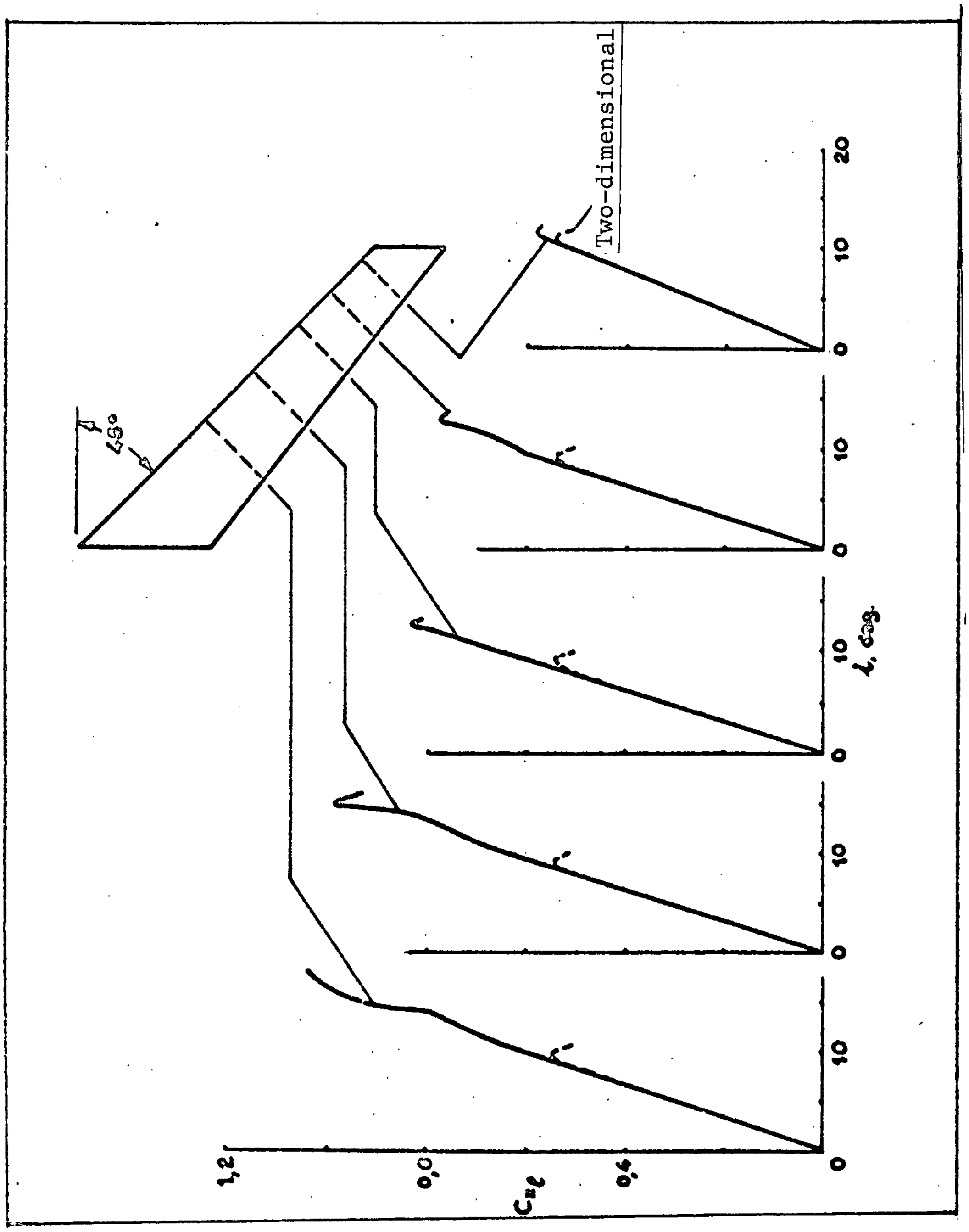


Plate 14. Comparison of experimental two and three-dimensional C_{zl} (i) curves (NACA Profile 64 A 010).

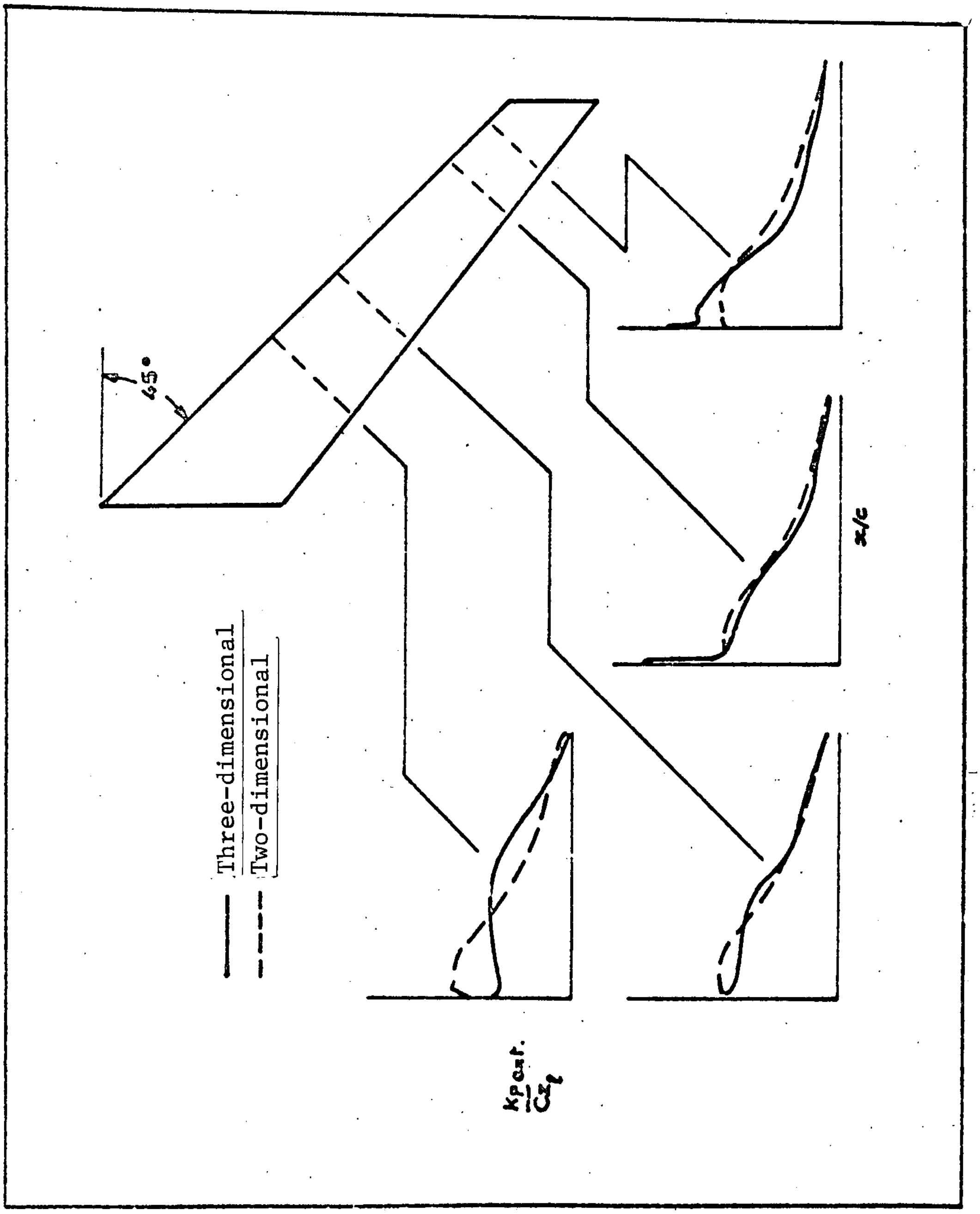


Plate 15. Comparison of two- and three- dimensional pressure measurements.

Prediction of Characteristics

Axelson's Method

Comparison of Experimental and Theoretical Results

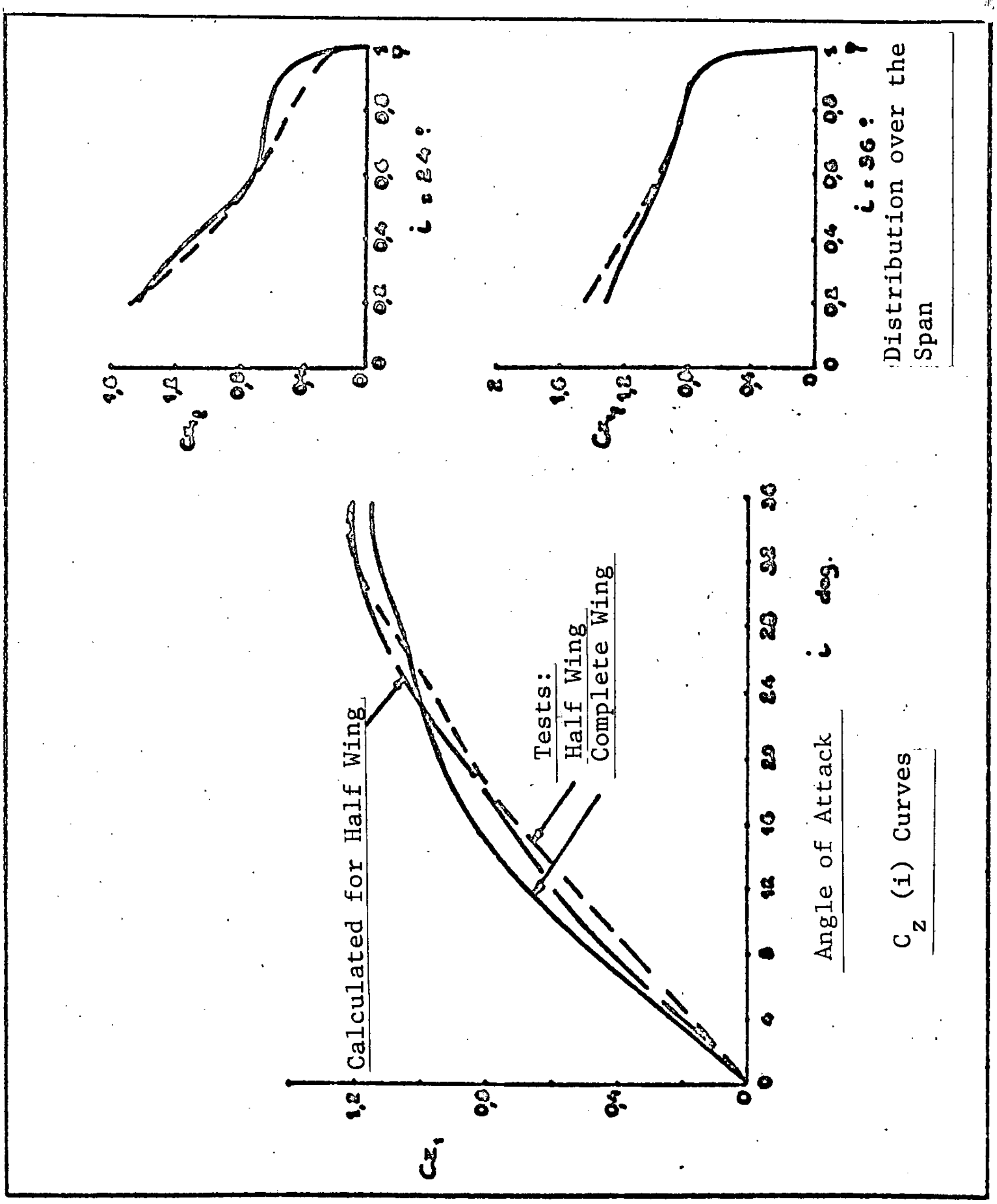


Plate 16

tips). It seems that from now on an acceptable prediction of $C_{z\ max}$ is possible for a moderately long and moderately swept wings, with or without high-lift devices. This prediction becomes more difficult as the sweep increases and as the length decreases. For this type of wing, the first-critical-section method provides at least qualitative results on the behavior of the wing at high angles of attack. In the most general case of a wing with arbitrary plan shape, fitted with a high-lift device and operating near maximum lift, there is not (to our knowledge, at least) any method of calculating the load distribution. Substantial theoretical and experimental work would thus be desirable to improve the qualities of high-lift wings. The theoretical study would obviously be difficult, yet the computational methods which are available, the boundary-layer theories which now exist or are being developed (Noel, Hirsch, Michel, et al.), and flow models which have been studied recently (Sachs, Taganov, et al.) give hope that these studies are possible.

IV. WING FITTED WITH "CLASSICAL" HIGH-LIFT DEVICES /19

4.1. General Discussion

The wing is equipped with high-lift devices at the leading and trailing edges. The problem is, first, the determination of the values of ΔC_z due to these devices; second, the determination of the value of $C_{z\ max}$ including that of the smooth wing.

4.2. $C_{z\ max}$ For Smooth Wing

4.2.1. Profile

A profile is given by its geometric characteristics:

curvatures: reduced radius at the leading edge, the mean radius of Ville and Wanner $\bar{r} = r\sqrt{1 + \frac{y_5^6}{10^3\, r^2}}$, with the ordinate y_5 at 5% of the leading edge.

thickness: maximum relative thickness e, and the reduced abscissa at this maximum σ_e.

camber: maximum sweep of the frame c, and its reduced abscissa σ_c.

angle of the trailing edge.

Since the Mach and Reynolds numbers of the flow are known, the value of $C_{z\ max}$ in the two-dimensional case can be evaluated using several groups of empirical relations, in particular those of Bore and Boyd [30], the Douglas report [29], and Ville and Wanner [10]. The predictive methods of these authors have been applied to two profiles, one corresponding to tests of Nord Aviation [24], the other, to tests by R.A.E. [3]. These results are shown in Plate 17. The methods of Ville and of Bore and Boyd (which are more dependent on geometric characteristics) give results close to experiment.

Note that the slopes are taken equal to $2\pi \times 0.95$, and that the C_{z_0} /20
have been evaluated by assuming that the cambers had the aerodynamic properties of NACA cambers.

4.2.2. "Smooth Wing"

As above, we have applied the methods of Douglas and of Bore and Boyd to "NORD" and "RAE" wings, without setting the flaps (Plate 18). It should be noted that in the Douglas method, the wing geometry appears only in the sweep. The Bore and Boyd method gives results acceptable in practice for both cases.

4.3. Wing with High-Lift Device. Evaluation of ΔC_z

4.3.1. Product-of-Influences Method

For any of the aerodynamic coefficients C_x, C_z, or C_m, it seems possible (at least approximately) to use an expression of the form

Comparison of Prediction with Experiment

Wings

C_z (i) Curves

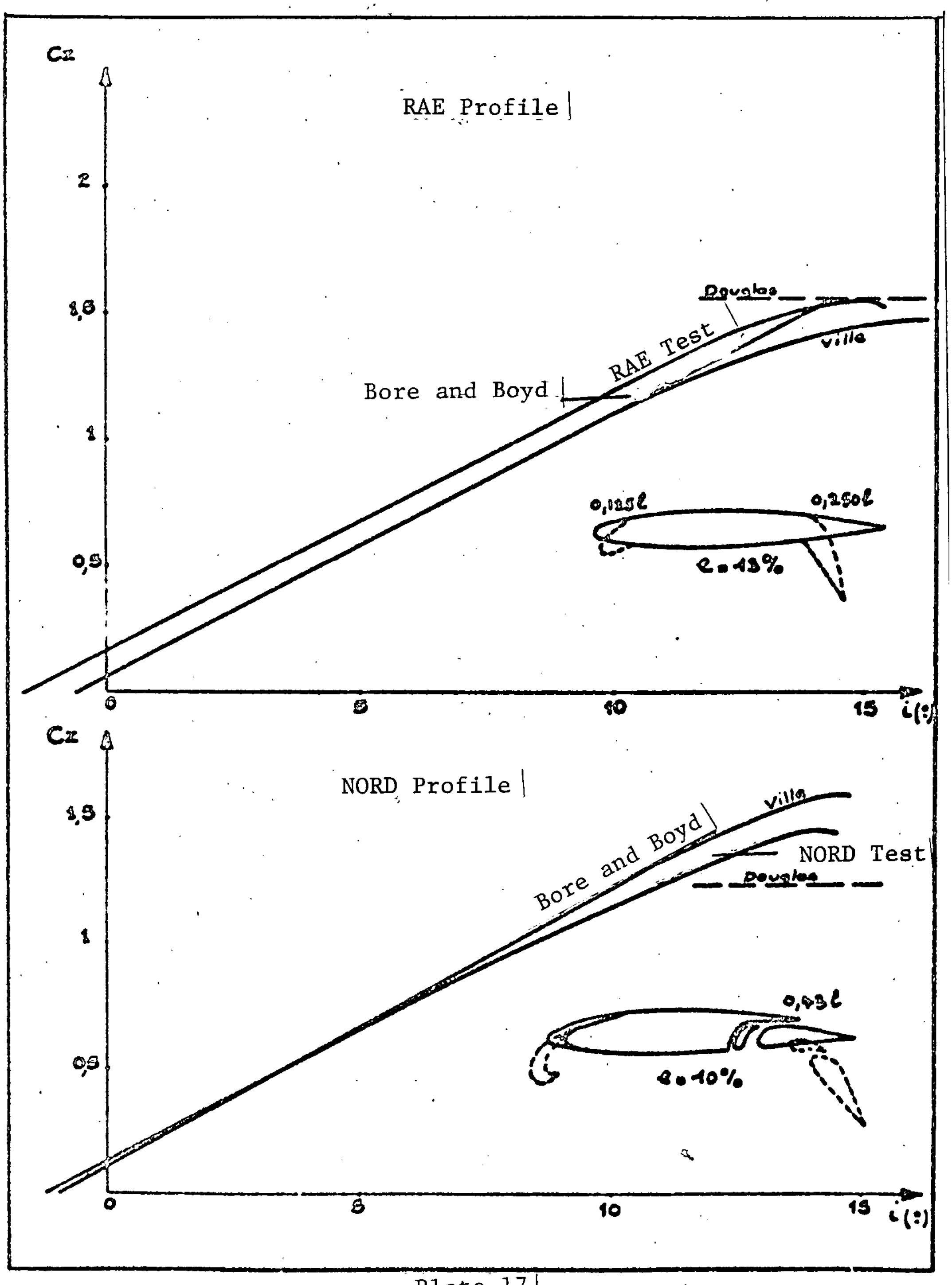


Plate 17

Comparison of Prediction with Experiment

Wings

C_z (i) Curves

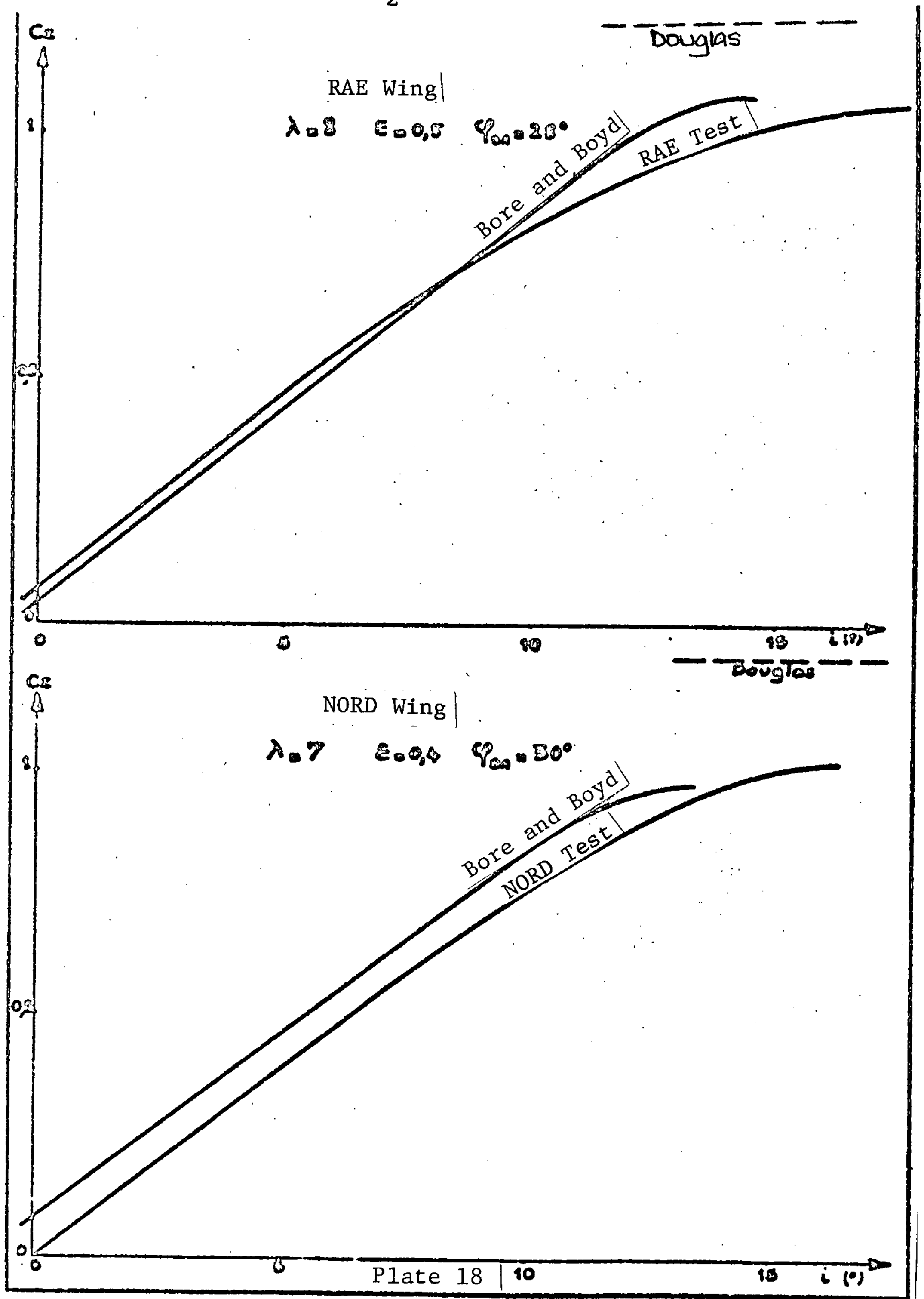


Plate 18

$$c = \prod_i f_i$$

where the functions f_i depend on the aerodynamic characteristics of the profile fitted with a flap (or of a reference wing fitted with this flap), on the geometeric characteristics of the wing, etc.

The methods of J. De Young [27], A. D. Young [28], and Lowry and Polhamus [25] allow calculation of ΔC_z for thin wings or for imposed profiles. As far as possible, we have used the two-dimensional results for application to Nord and RAE wings (Plate 19).

4.3.2. Empirical Method of Douglas

This method is particularly simple, since the transfer from two dimensions to three is accomplished for the trailing-edge flap by use of the fraction $\frac{S_p}{S_{ref}}$ of the surfaces concerned. For a leading-edge flap, the fraction $\frac{b_r}{b}$ of the affected spans is used. Furthermore, this procedure is especially interesting as it is easy to use the results of two-dimensional tests.

In Plate 19 this method is compared with the methods mentioned above; it is seen that the accuracy is better than 20% for the two wings. /21

4.4. $C_{z\ max}$ for Wing with High-Lift Device

It is assumed that $C_{z\ max} = (C_{z\ max})|_{\text{smooth wing}} + \Delta C_z$, where ΔC_z is due to the high-lift devices at the trailing and leading edges; one would thus like to write $\Delta C_z = \Delta C_{z_v} + \Delta C_{z_n}$. In reality, there is an interaction between the two high-lift devices, such that the individual increases in lift are smaller when the high-lift devices are operating simultaneously. According to Wimpenny [36],

$$\Delta C_z = k_v \Delta C_{z_v} + k_n \Delta C_{z_n}$$

with $k_v = 0{,}84$ and $k_n = 0{,}64$.

The value of ΔC_{z_n} is obtained for a slotted flap and for a leading-edge flap from [32].

Wing with High-Lift Device

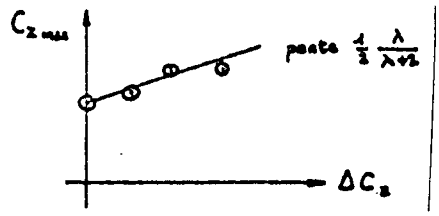
Comparison of Prediction with Experiment

Value of ΔC_z

Author (RAE)	Author (NORD)	Observations	RAE Wing ΔC_z	RAE Wing Δ %	NORD Wing ΔC_z	NORD Wing Δ %
Eyre & Butler	Lazareff & Lerbet	Experimental	1.16		1.5	
A. D. Young		Calculation by Young	0.98	-16	1.58	5
A. D. Young		Starting from Experimental $C_{z\ 2D}$	0.84	-28	1.52	1.3
Douglas		"Douglas" Calculation	1.265	+ 9	1.235	-17
Douglas		Starting from Experimental $C_{z\ 2D}$	0.975	-16	1.71	+14
[J. De Young		Flat Plate	2.23		1.81]	

Plate 19

Plate 20 shows the results of calculations by the Wimpenny and the Douglas methods, compared to experimental results on Nord and RAE wings. The result of a calculation by McRae's method [35] is also shown.



This method provides values of $C_{z\ max}$ when ΔC_z is known, using a very simple correlation based on the theory of thin profiles, and using only the function

$\left.\frac{1}{2}\frac{\lambda}{\lambda+2}\right|$ to characterize the wing.

Wing with High-Lift Device

Comparison of Prediction with Experiment

Value of $C_{z\ max}$

Author		Observations	RAE Wing		NORD Wing	
RAE	NORD		$\Delta C_{z\ max}$	$\Delta\%$	$\Delta C_{z\ max}$	$\Delta\%$
Eyre & Butler	Lazareff & Lerbet	Experimental	2.17		2.77	
Douglas		"Theoretical" Values	2.43	+12	2.27	-18
Douglas		Experimental values of $C_{z\ max}$ for smooth wing Experimental values of $\Delta C_{z\ 2D}$ Theoretical values of $(\Delta C_z)_N$	2.32	+ 7	2.13	-23
Wimpenny		Experimental values of $C_{z\ max}$ for smooth wing Experimental values of $\Delta C_{z\ 3D}$ Datcom values of $(\Delta C_z)_N$	2.3	+ 6	2.32	-16
McRae		" " " "	2.29	+5.5	2.38	-14

Plate 20

4.5. Partial Conclusions /22

As might be expected, the methods of Wimpenny and of McRae give values for these two wings which are closest to test results. It should be noted, however, that in the cases considered, the maximum error can be of the order of $\pm$ 15%.

V. HIGH-LIFT DEVICES USING BLOWING /23

5.1. General Discussion of Blowing

5.1.1. Description

Plates 21, 22, and 23 show various blowing methods. In general, it is a matter of obtaining high lift by the action of a jet on a wall. This jet can be produced by a fan (Breguet 941), or by an engine jet blowing directly onto flaps (direct blowing). There can also be a more or less large diversion of air or engine gases (indirect blowing), and blowing at the leading or trailing edges (boundary-layer control, fluid flap, aspirated flap, etc.).

A number of blowing devices are assembled in Plate 21. One of them combines blowing by fan with boundary-layer entrainment by a mechanical device (Alvarez-Calderon). The device for lateral blowing (studied by Dixon, and separately by Onera) seems very especially interesting from the fluid mechanics standpoint: action of a jet on detachment when the jet is perpendicular or oblique to the velocity at infinity. It also seems that this device could be of practical interest because of the considerable simplification of the air-supply ducting.

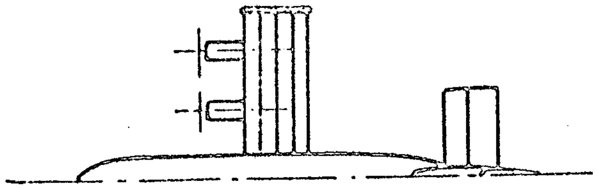
Plate 22 shows some devices for direct blowing from NASA [6, 7, 34] and Nord Aviation [8], while Plate 23 shows some forms of slots for leading- and trailing-edge blowing (Gratzer, [33]).

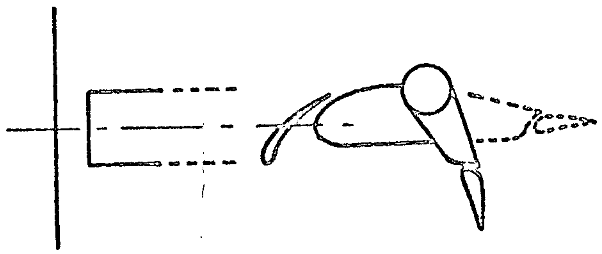
5.1.2. Review of Blowing Problems /24

Fluid-mechanics phenomena

Whatever the blowing system, a jet acts on the flow:

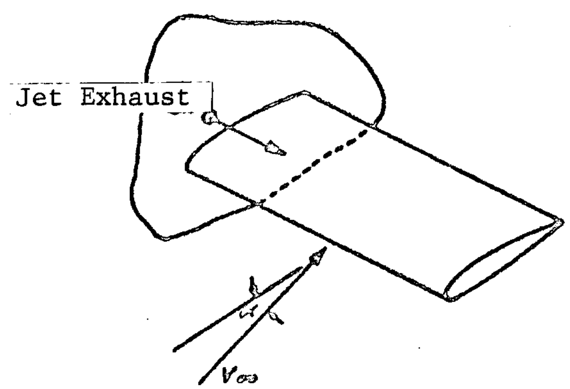
High-Lift Devices Using Blowing.

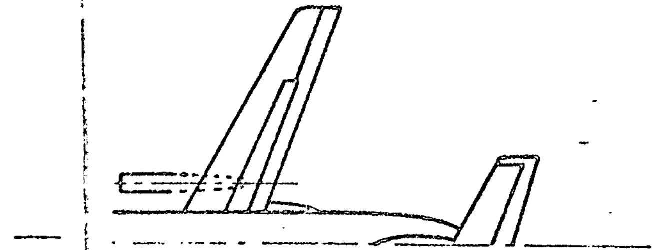




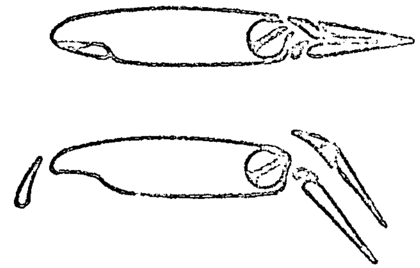
Direct Blowing
ALVAREZ CALDERON Method

Lateral Blowing (Dixon)

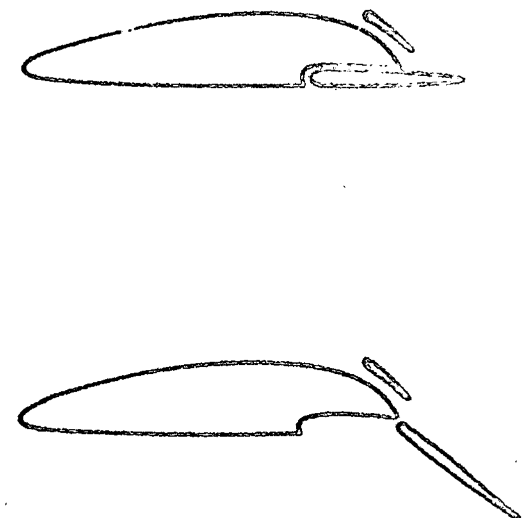




Aspirated Flaps



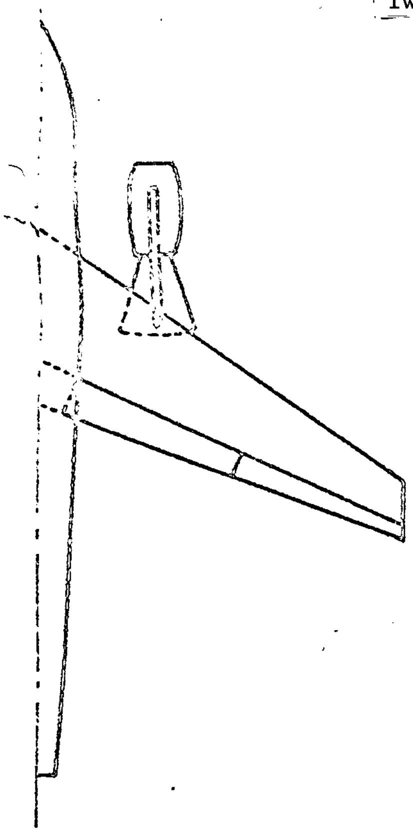
Aspirated Flap
DE HAVILAND - CANADA

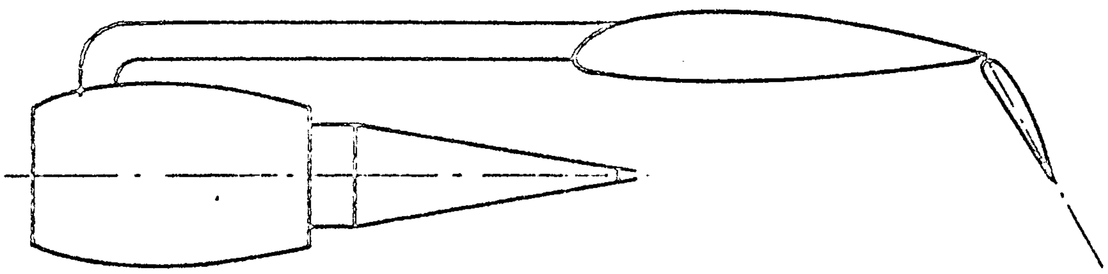


Aspirated Flap
System of W. S. Campbell

Two Engines - Flattened Nozzle

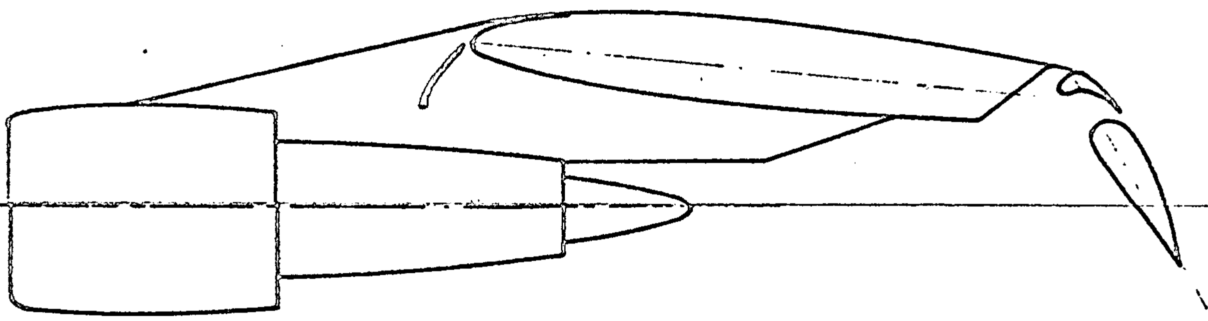
NASA TN D 643

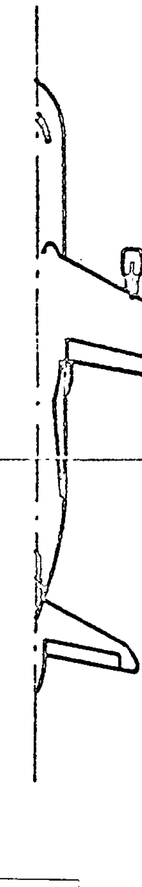




Four Engines - Classic Engine Positions

NASA TN D 4020



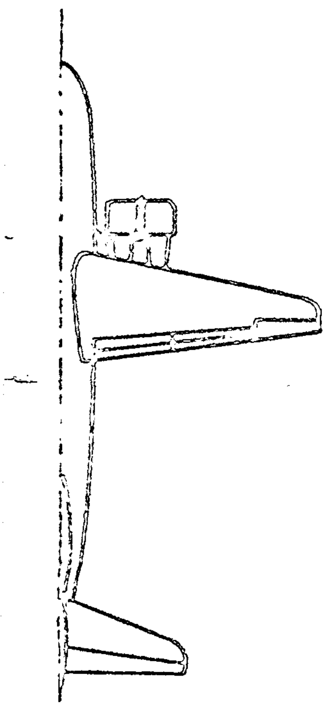


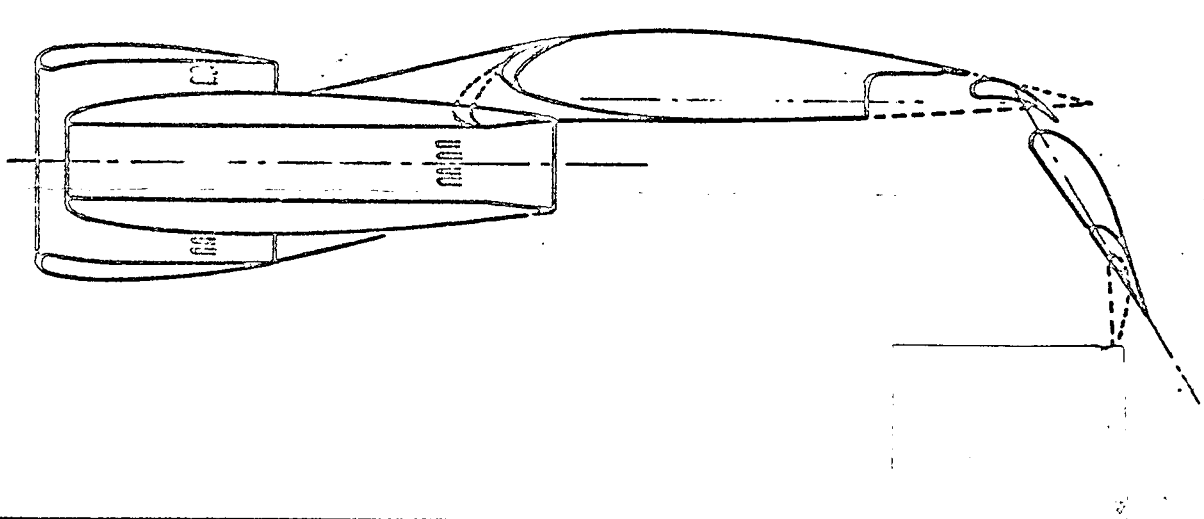
High-Lift Devices - Direct Blowing

Plate 22

Four Engines - Close-in Nacelles

NASA TN D 6364





Curved Flap Blown by Engine Jet

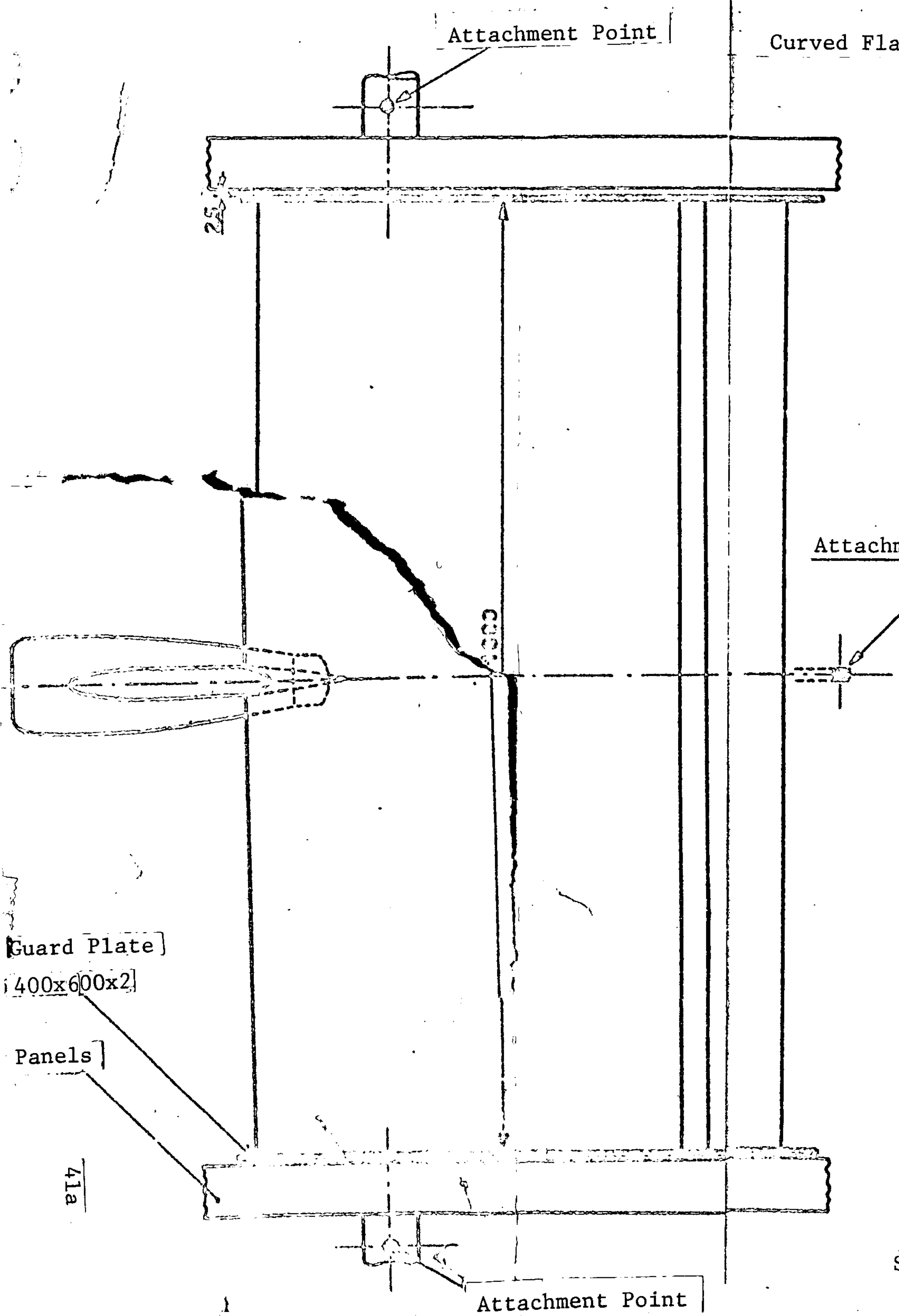


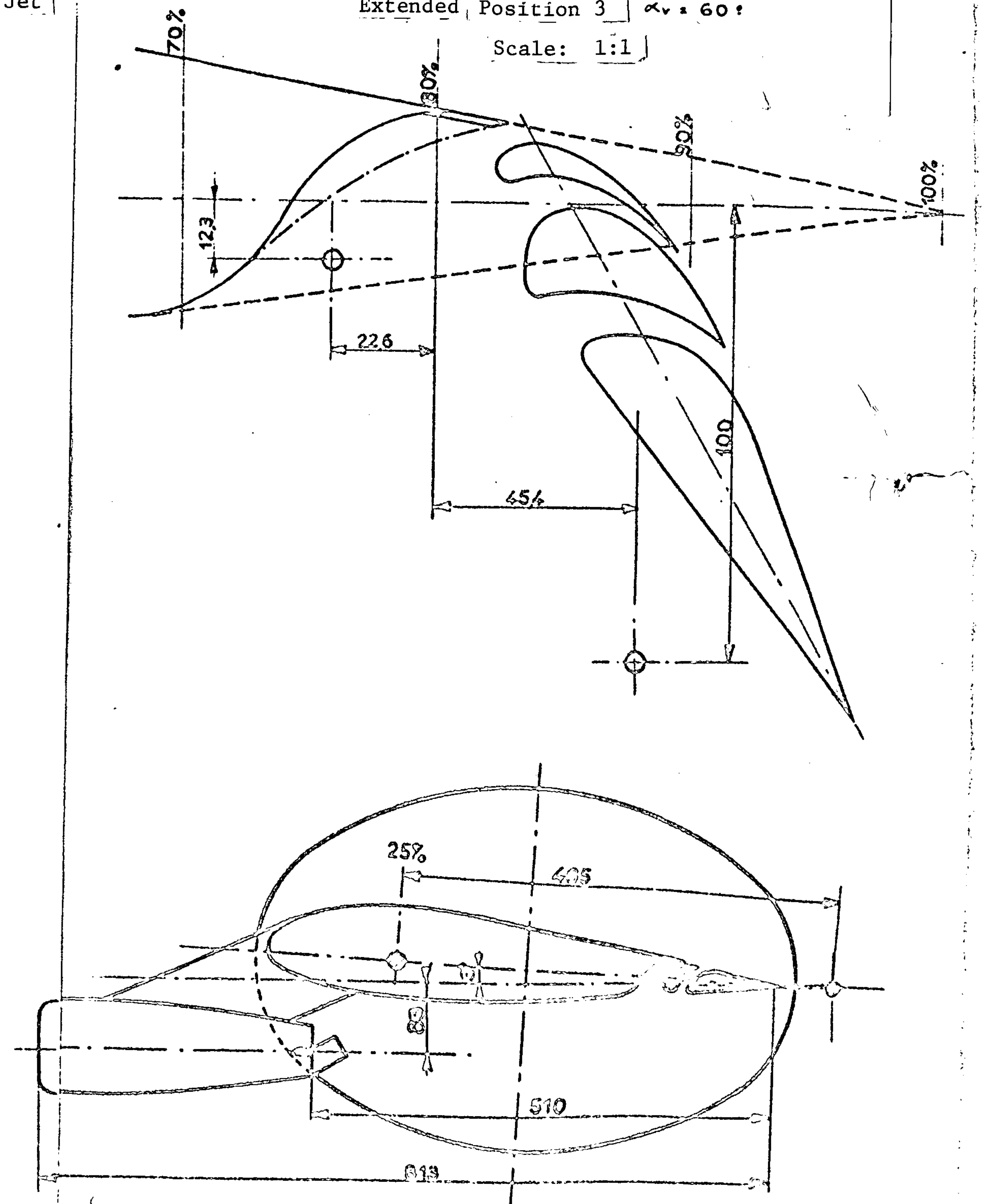
Plate 22

Scale: 1/5

Flap 2

Extended Position 3 $\alpha_v = 60°$

Scale: 1:1



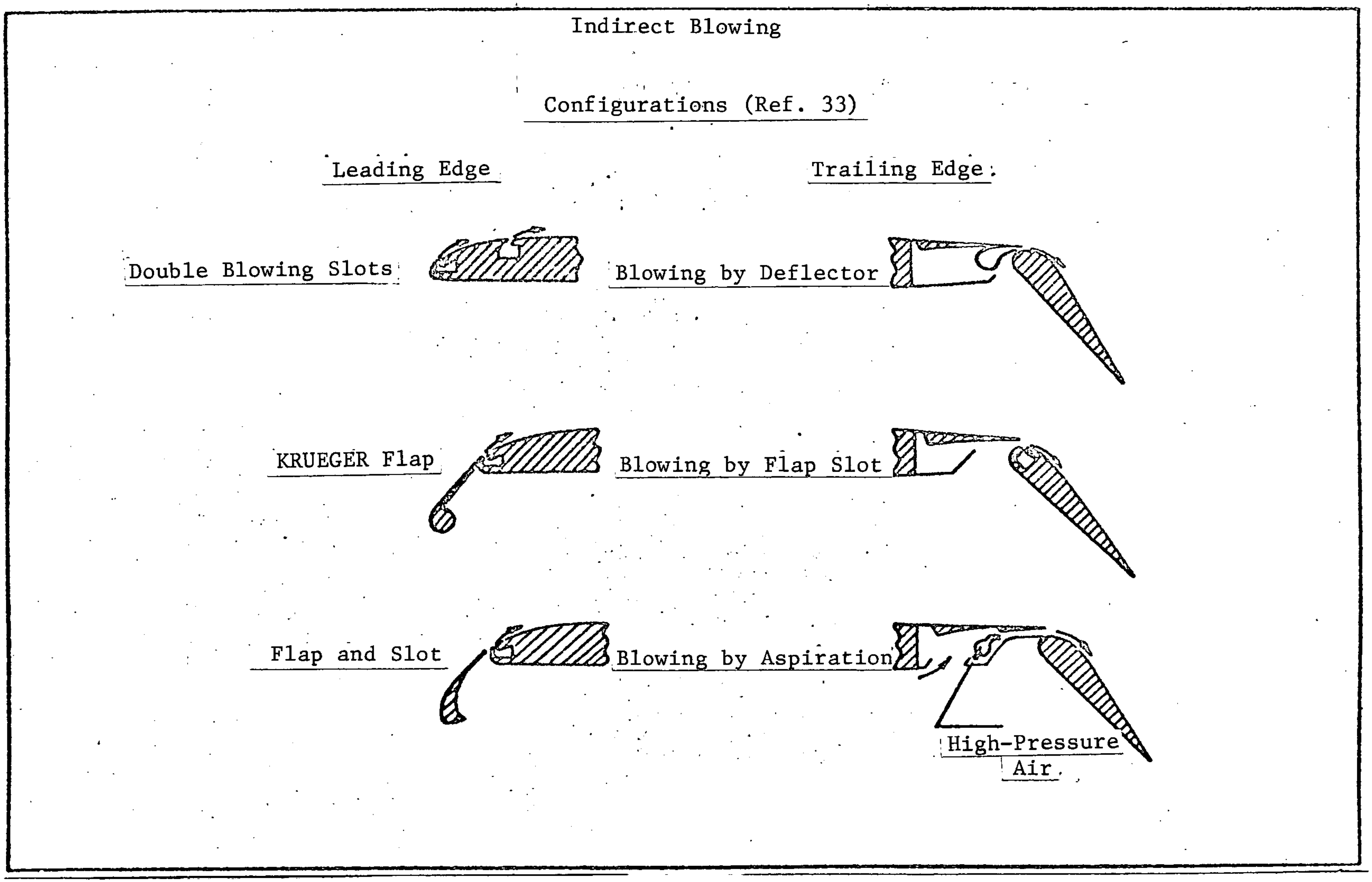

Indirect Blowing
Configurations (Ref. 33)
Leading Edge
Trailing Edge
Double Blowing Slots
Blowing by Deflector
KRUEGER Flap
Blowing by Flap Slot
Flap and Slot
Blowing by Aspiration
High-Pressure Air

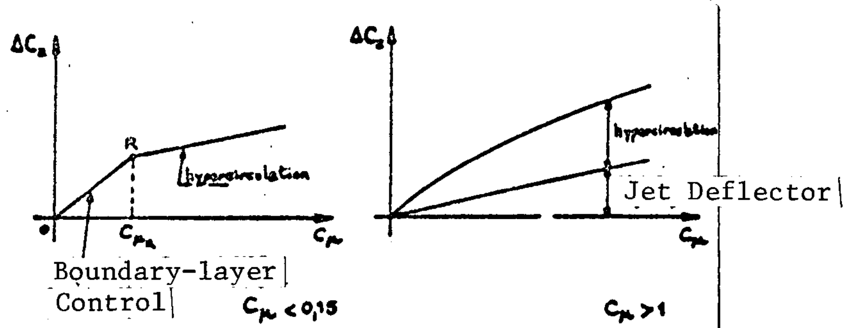
Plate 23

- by boundary-layer control ($C_\mu < C_{\mu R}$) with $C_\mu = \frac{\dot{m}_j V_j}{qS}$, where $C_{\mu R}$ is the value of C_μ for re-attachment.

- by hypercirculation ($C_\mu > C_{\mu R}$). The jet increases the velocity at the wall, which results in a variation in circulation $\Delta\Gamma = \Delta(\int V.ds)$ and the corresponding value of ΔC_z : $\Delta C_{z\Gamma}$

- by jet deflection. If δ_j is the angle of the jet with the aircraft axis, there is a lifting force $\dot{m}_j V_j \sin(\delta_j + i)$ and a lift coefficient ΔC_{z_d}

In general, the type of lift obtained varies with the C_μ level:



Indirect blowing generally leads to momentum coefficients C_μ of the order of 0.1; direct blowing, to coefficients of the order of 1 to 4.

Problems of flight mechanics /25

- Equilibrium and longitudinal stability
  These problems obviously exist for conventional high-lift devices; they can become more complicated for blowing, however, because of the action of the jet on the turbulent slipstream (a large variation in deflection).

- Course stability
  It should be noted that large variations in the intensity of turbulence along the span can produce vortices relatively close to drift, and thus

affect course stability.

- Ground effect

  Plate 3 (from Gersten [5]) shows that the presence of the ground can considerably modify the value of ΔC_z obtained by blowing, and that there is a threshold (h/l > 1.4) where the flow is no longer influenced by the ground.

5.1.3. Results for Different Types of Blowing

Some results for internal blowing are gathered in Plate 24. They include results of Gratzer [33] for blowing separately at the leading and trailing edges, and results from R.A.E. [2] for simultaneous blowing at the upstream and downstream ends of the profile.

The table below gives some orders of magnitude of $C_{z\ max}$ for several blowing devices.

Type of High-Lift Device	$C_{z\ max}$	C_μ
Breguet 941	5	$C_T \sim 1$
Alvarez-Calderon [41]	10	$C_T \sim 3.5$
Aspirated Flap [42]	6	1
Lateral Blowing [*]	3.6	1
Direct Blowing [7]	5	3

/26

*Translator's Note: Illegible.

Indirect Blowing

$C_{z\ max}$ as a Function of C_μ

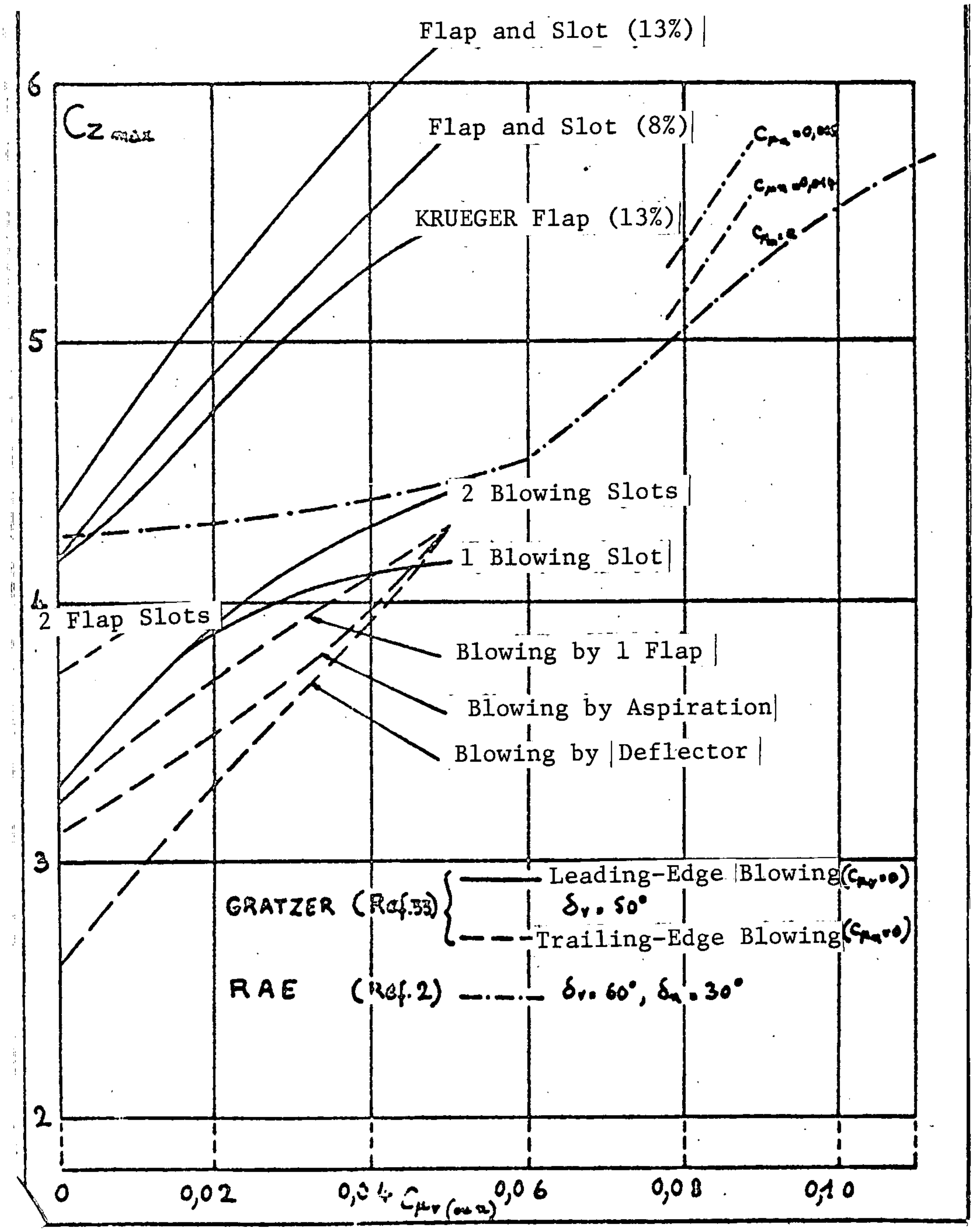


Plate 24

5.2. Problems of Indirect Blowing

5.2.1. Discussion

In addition to the flight-mechanics problems mentioned above, it should be noted that the choice and arrangement of a high-lift device using indirect blowing depend particularly on the possibility of engine failure. It is also necessary to "optimize" the high-lift device, among other things consistent with finding a mass flow distribution between the forward and aft slots which will correspond to the greatest value of ΔC_z for an over-all value of C_μ.

Finally, it is above all a matter of predicting the value of ΔC_z (C_μ); we note immediately that this prediction concerns (to our knowledge) only trailing-edge blowing. We shall discuss later the problems of prediction as they now occur.

Investigation of $C_{\mu R}$

At the re-attachment point R, C_z assumes approximately its theoretical value. This is the junction of two regimes: boundary-layer control, and high-lift. The value of $C_{\mu R}$ apparently depends on a fairly large number of parameters: geometry of the blowing slot, geometry of the wing and of the flap and its angle δ_v, Reynolds number, etc. Values of $C_{\mu R}$ (δ_v) will be given in § 5.2.2.

The Functions ΔC_z (C_μ) /27

The approximation $C_z = a\ (C_\mu)^b$ is used, with the constants a and b depending on the regime considered.

Passing to the Three-Dimensional Case

It is generally assumed that at point R, the value of ΔC_z is that of the three-dimensional case without blowing, for example, that given by J. De Young [27] or Lowry and Polhamus [25]. Here again, one must go from $C'_{\mu R}$, which is obtained in a two-dimensional experiment, to the value of $C_{\mu R}$ which is adopted in the three-dimensional case. The formula $C_{\mu_R} = C'_{\mu R} \frac{S_\ell}{S} \cos^2 \varphi_{ch}$, is used, in which the flap geometry is characterized only by the sweep ϕ_{ch} of the hinge. The ratio $\frac{S_\ell}{S}$ is the fraction of the wing surface affected by blowing. It can be seen that the wing geometry (λ, ϕ, ε) and its angle of attack are not involved.

5.2.3. Results

Effect of Slot Height

Plate 25 compares a certain number of experimental values of $C_{\mu R}$ (δ_v) with empirical laws. There is a certain dispersion which can be attributed at least partially to an effect of slot height. It can also be noted that the aspect ratio of the wing has an effect which cannot be neglected.

Interference of fore and aft slots

When the two blowing slots are operating at the same time, one can expect coupling of the two flows. Intuitively, one would expect a decrease in $C_{\mu R}$ downstream (on the trailing-edge flap) when the leading edge is blown; experiments cited by Gersten and Loehr [5] show precisely the opposite effect (Plate 26).

With a profile with an angled leading edge (RAE tests, [2]), the coupling /28 seems to be canceled, or possibly changes in sign.

C_μ Corresponding to Re-attachment

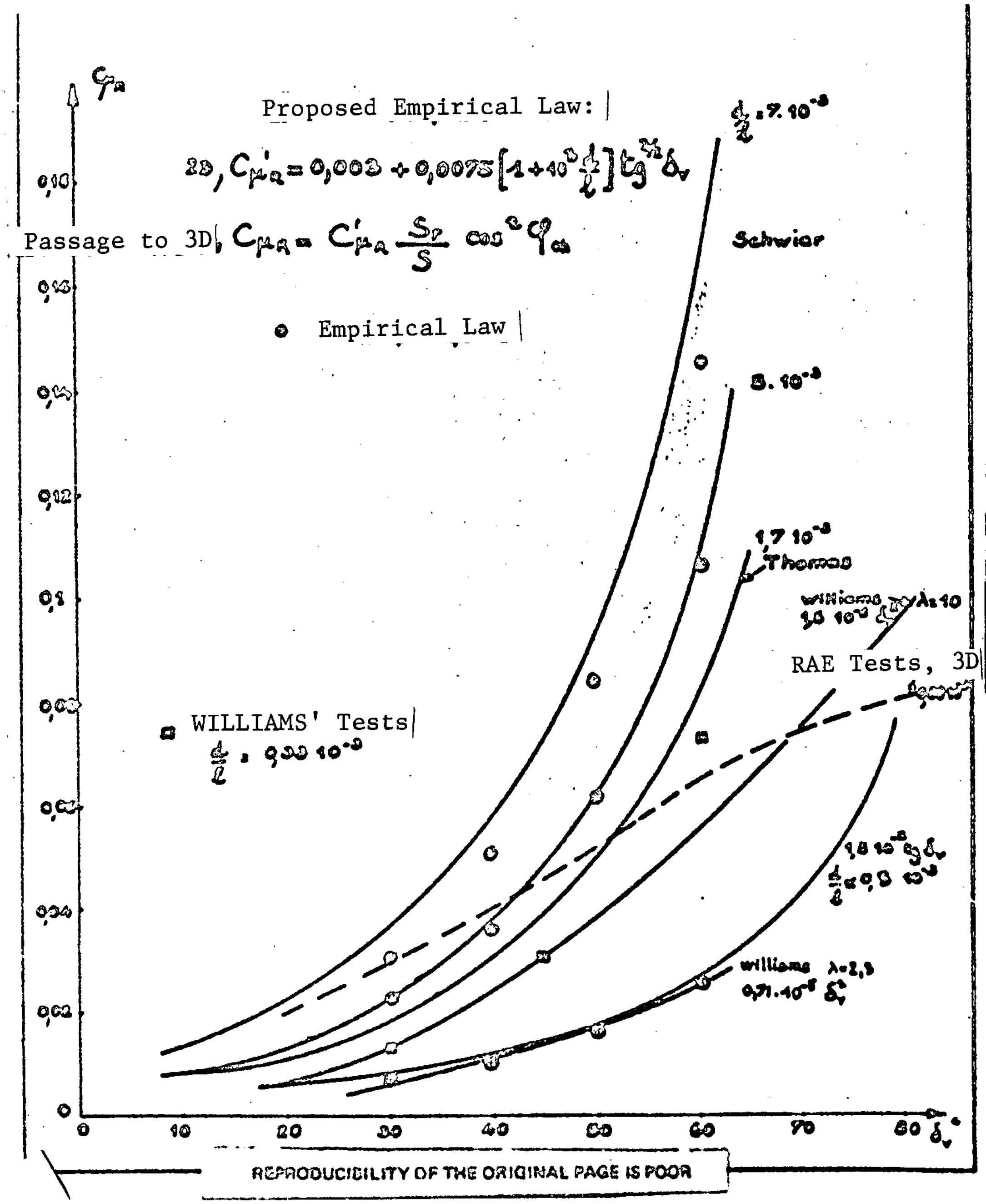


Plate 25

C_μ Corresponding to Re-attachment

δ_v	RAE Tests		RAE Calcul-ations	Prediction
	2 D	3 D $\frac{S_p}{S}$		$C'_{\mu a} = 1{,}5 \cdot 10^{-5}\,\delta_v^2$
20	0,0214			0,006
40	0,0466	0,04	0,05	0,024
60	0,067	0,065	0,064	0,054
80		0,08	0,086	0,096

Plate 25a

Indirect Blowing

Interference of Forward and Aft Slots

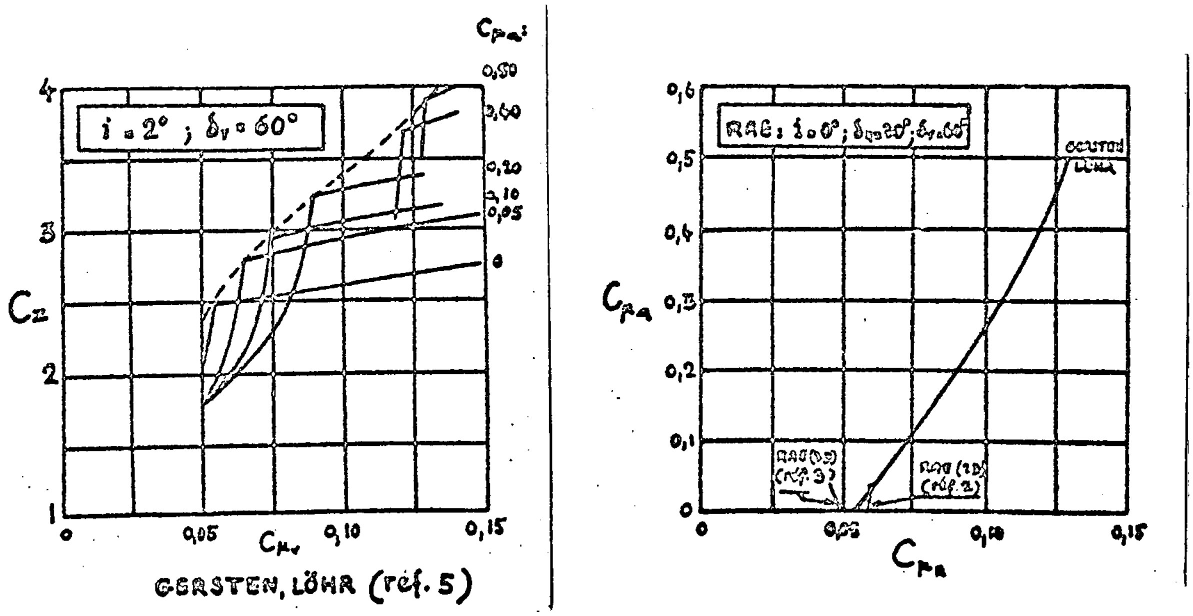


Plate 26

Optimal value of the ratio $C_{\mu n}/C_{\mu g}$

The question can be asked: in what proportion is it necessary to blow the leading edge? According to Gersten (Plate 27), with constant total blowing, to have the largest C_z it is necessary that $C_{\mu n}/C_{\mu g} \sim 0.5$. The RAE data on the same plate do not show any really clear optimum.

5.2.3. Example of Application

It is interesting to see to what extent the results of two-dimensional tests can be used for the prediction of wing characteristics. The results of RAE wind tunnel tests on a profile [2] and on a wing [3] of the same profile should be able to give an example of this type of prediction.

In Plate 28 the experimental curve for C_z (C_μ) obtained at RAE for $\delta_v = 60°$, $\delta_n = 30°$, and $C_{\mu n} = 0$ is compared with:

- a curve obtained by using the value $(\Delta C_{z\ 2D})_R$ at the re-attachment point to obtain $(\Delta C_{z\ 3D})_R$, as well as the corresponding value of $C'_{\mu R}$ (two-dimensional) to obtain $C_{\mu R}$ by the formula given above.

- a curve obtained by using the value of $(\Delta C_{z\ 3D})_R$ given by J. De Young [27] and the value of $C'_{\mu R}$ obtained from the formula given by Poisson-Quinton [1].

In each case ΔC_z (C_μ) was chosen as follows: for $C_\mu < C_{\mu R}$, the straight line segment OR for $C_\mu > C_{\mu R}$, a curve of the form $\Delta C_z = a\ (C_\mu - C_{\mu R})^b$, with $b = 1/3$ (Prediction 1) or $b = 1/4$ (Prediction 2).

In this particular case, it appears that whichever method is used will /29
give an acceptable result. It would of course be necessary to have other examples to be able to draw any useful conclusions, but it seems that the case examined would justify to some extent the method of going from the two- to the

Indirect Blowing

Optimum Value of the Ratio $\frac{C_{\mu n}}{C_{\mu g}}$

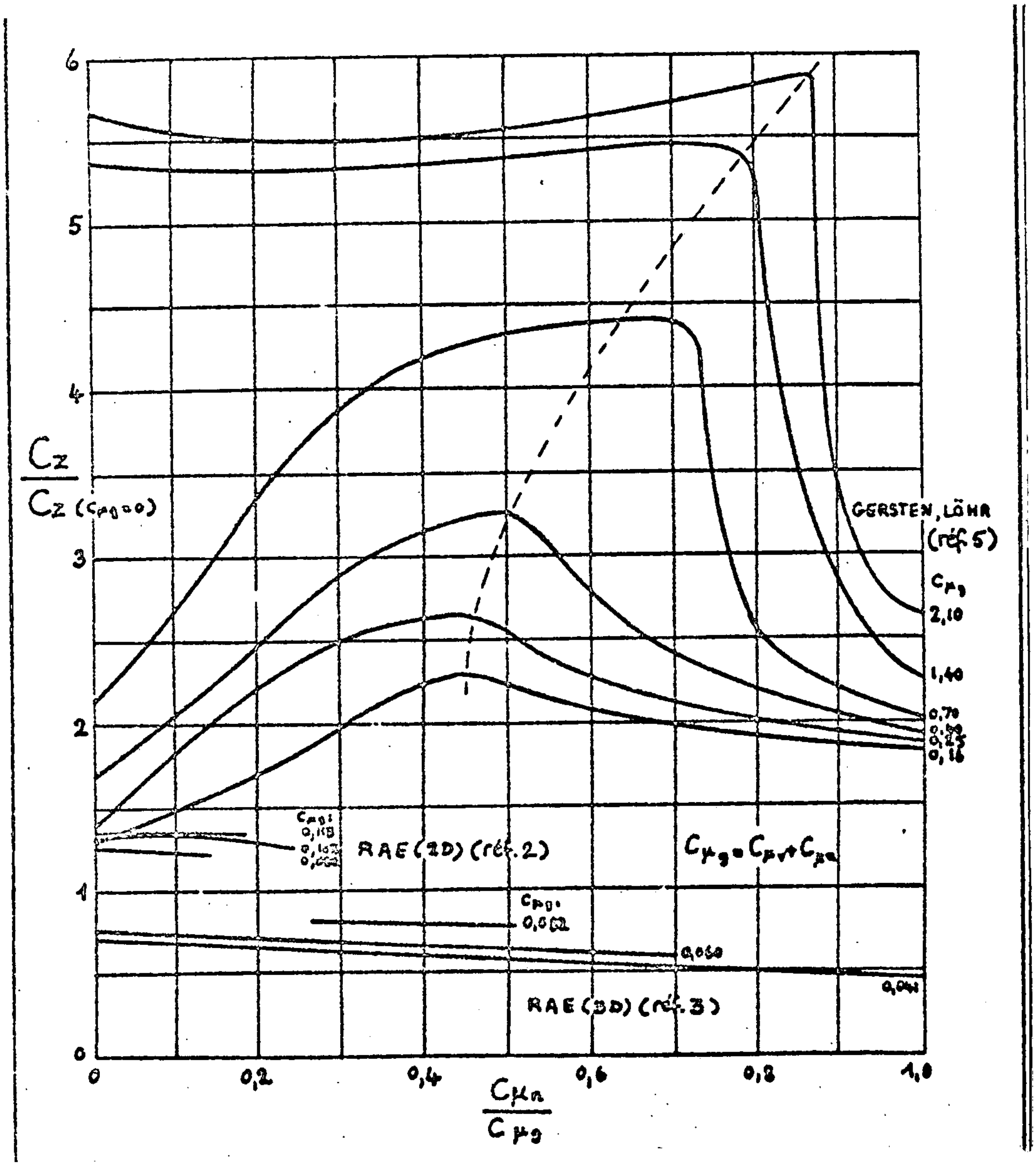


Plate 27

Comparison of Prediction with Experiment

Indirect Blowing

ΔC_z (C_μ) Curves

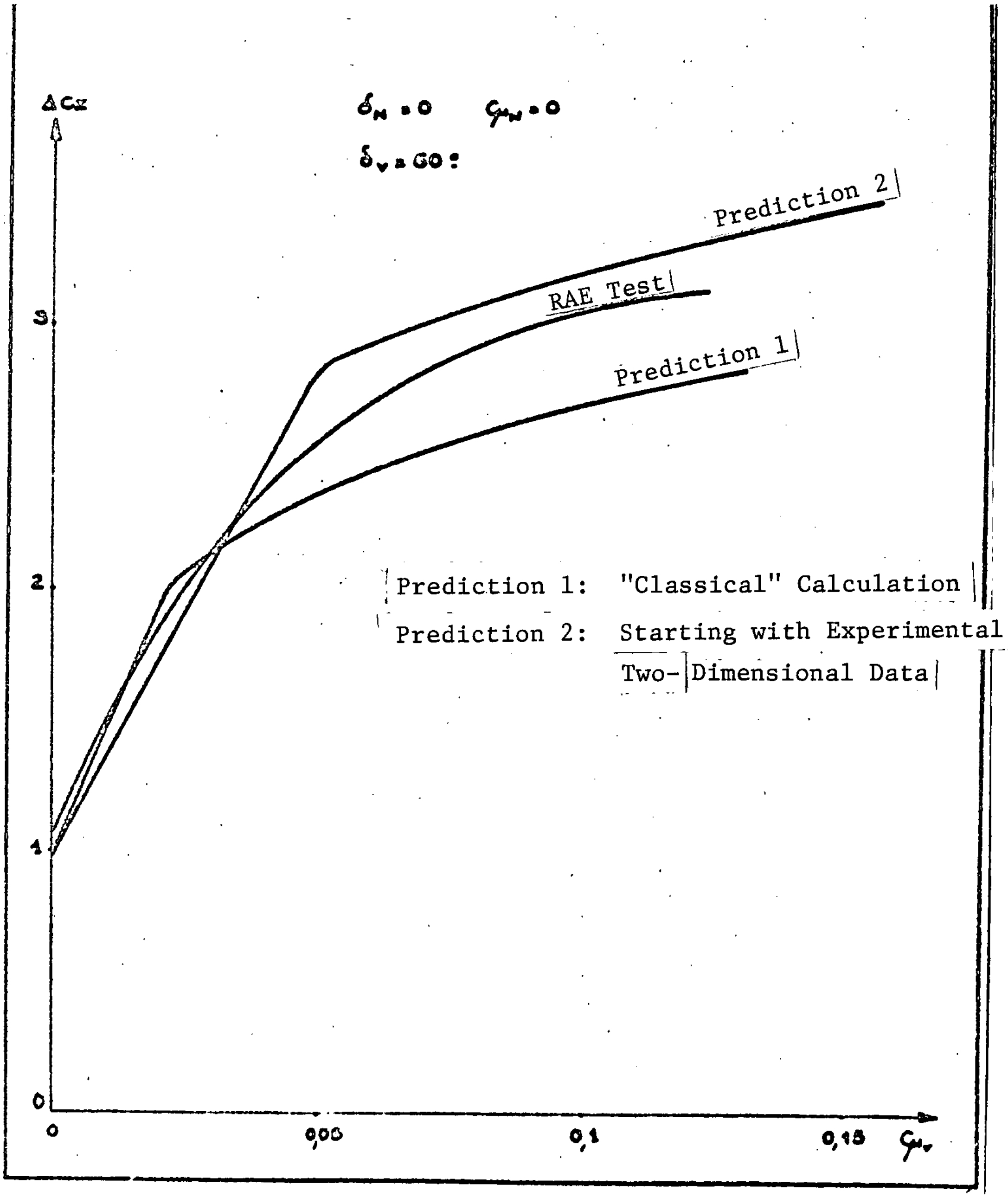


Plate 28

three-dimensional values, for wings of moderate sweep and aspect ratio.

The curve of Plate 29 was obtained by using the experimental ΔC_z (C_μ) curve and McRae's method [35]. The experimental curve, also shown, agrees well.

5.3. Problems of Direct Blowing

5.3.1. Description of Some Designs

Plate 22 shows several installations which differ particularly:

- by engine position — distant or close in, etc.
- by nozzle shape — flattened or not, with or without deflector, etc.
- by flap shape.

5.3.2. Presentation of Results

The "quality" of an installation is shown by, among other things, its capability to deflect a jet (Plate 31) and by the increase $\Delta C_{z\Gamma}$ in C_z obtained by high lift (Plate 30).

If one considers the angle θ defined by $\theta = \delta_j - \delta_v$, it will be seen that an installation will give a better deviation as θ becomes larger (algebraically), i.e., as δ_j becomes as large as possible for a given flap setting δ_v. The value of θ depends strongly on the adaptation of the flap to the engine jet.

Plate 31 shows the tests of Parlett and Shivers [7], with $\theta > 0$, close-in engines, and rather evolved flaps. This Plate, a polar diagram, shows the thrust (thrust modulus) as a function of δ_j. /30

5.3.3. Remarks on the Distance of Engines on the Span

The possibility of engine failure requires, in the case of direct blowing, not only use of four engines, but possibly use of close-in engines (their

Comparison of Prediction with Experiment

Indirect Blowing

$C_{z\ max}\ (C_{\mu})$ Curves

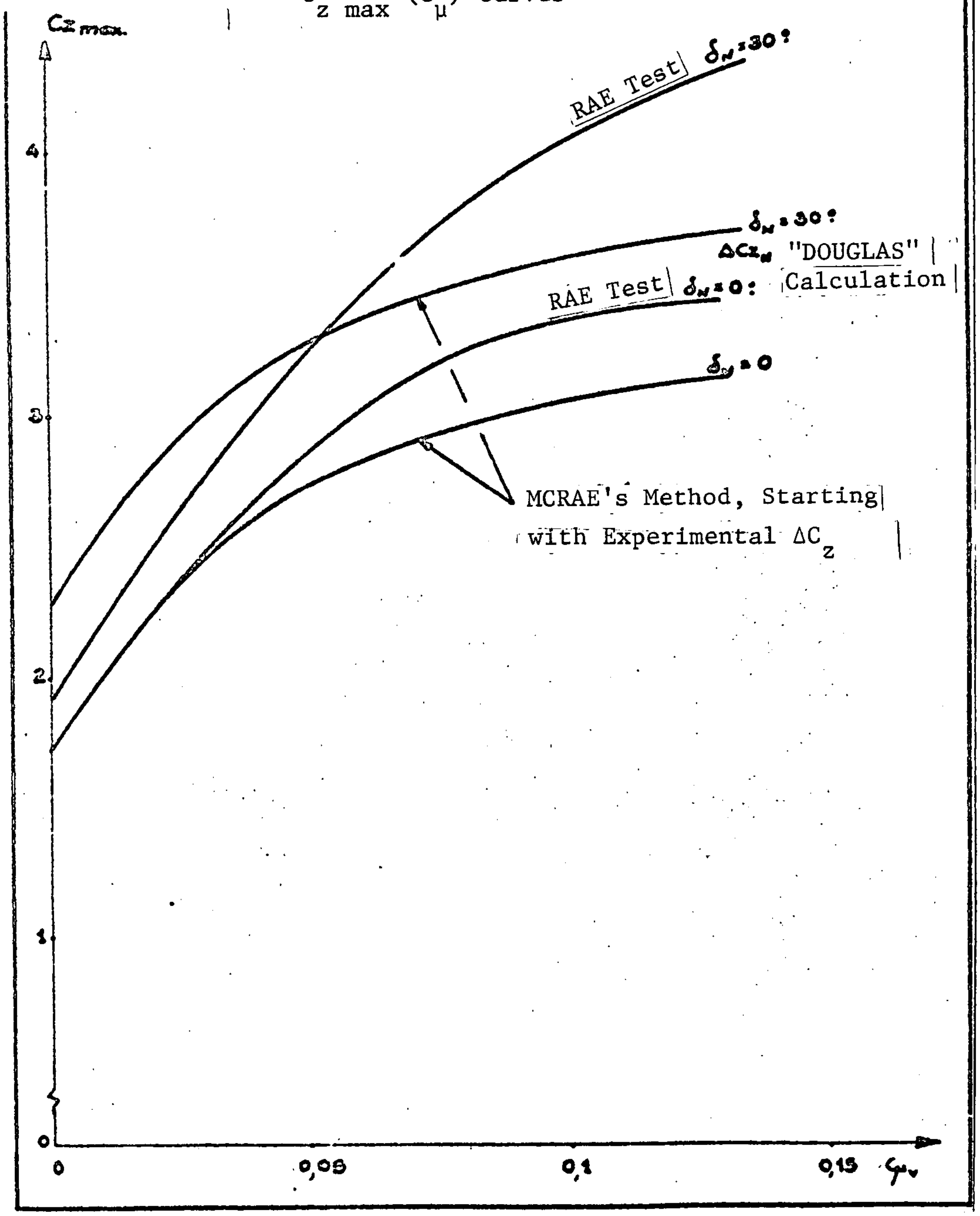


Plate 29

Lift by Hypercirculation

As a Function of the Blowing Coefficient C_μ

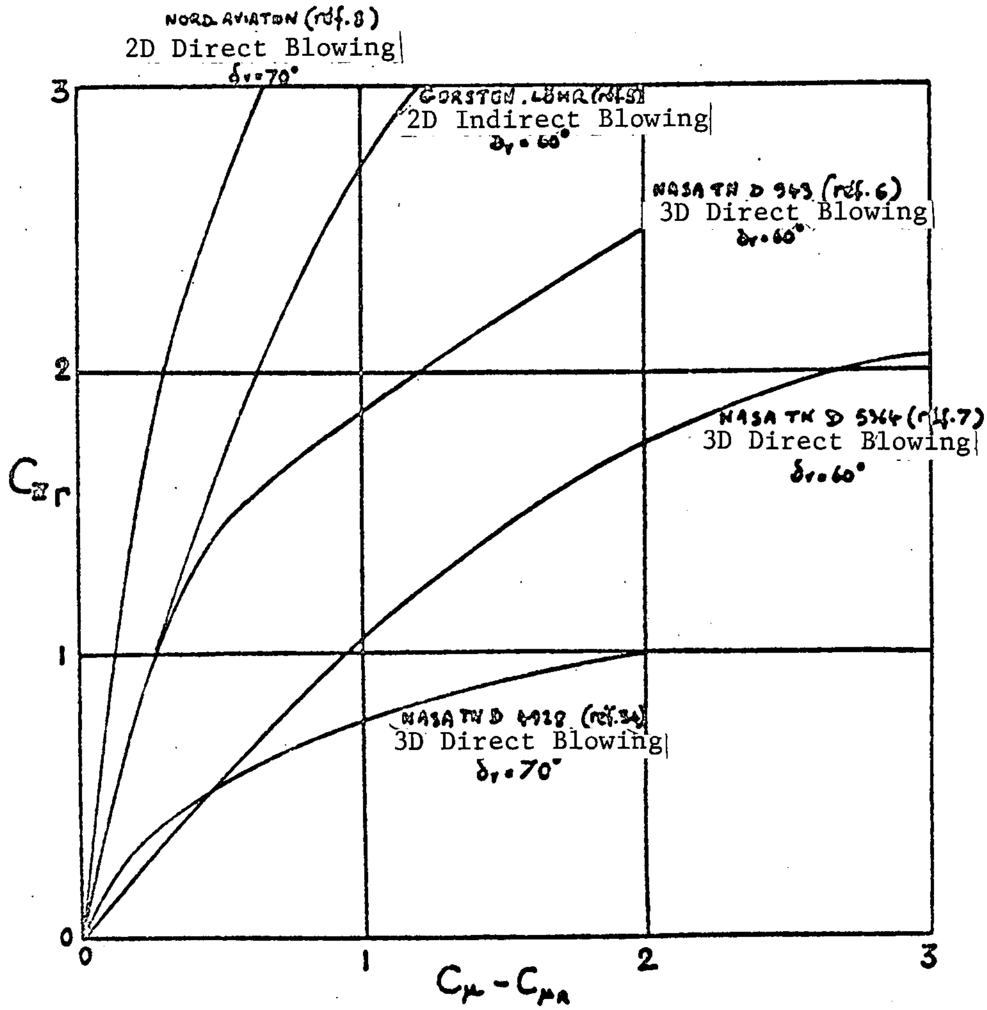


Plate 30

Direct Blowing

Deviation δ_j and Efficiency η of Engine Thrust Deflected by a Trailing-Edge Flap. δ_v is Flap Setting

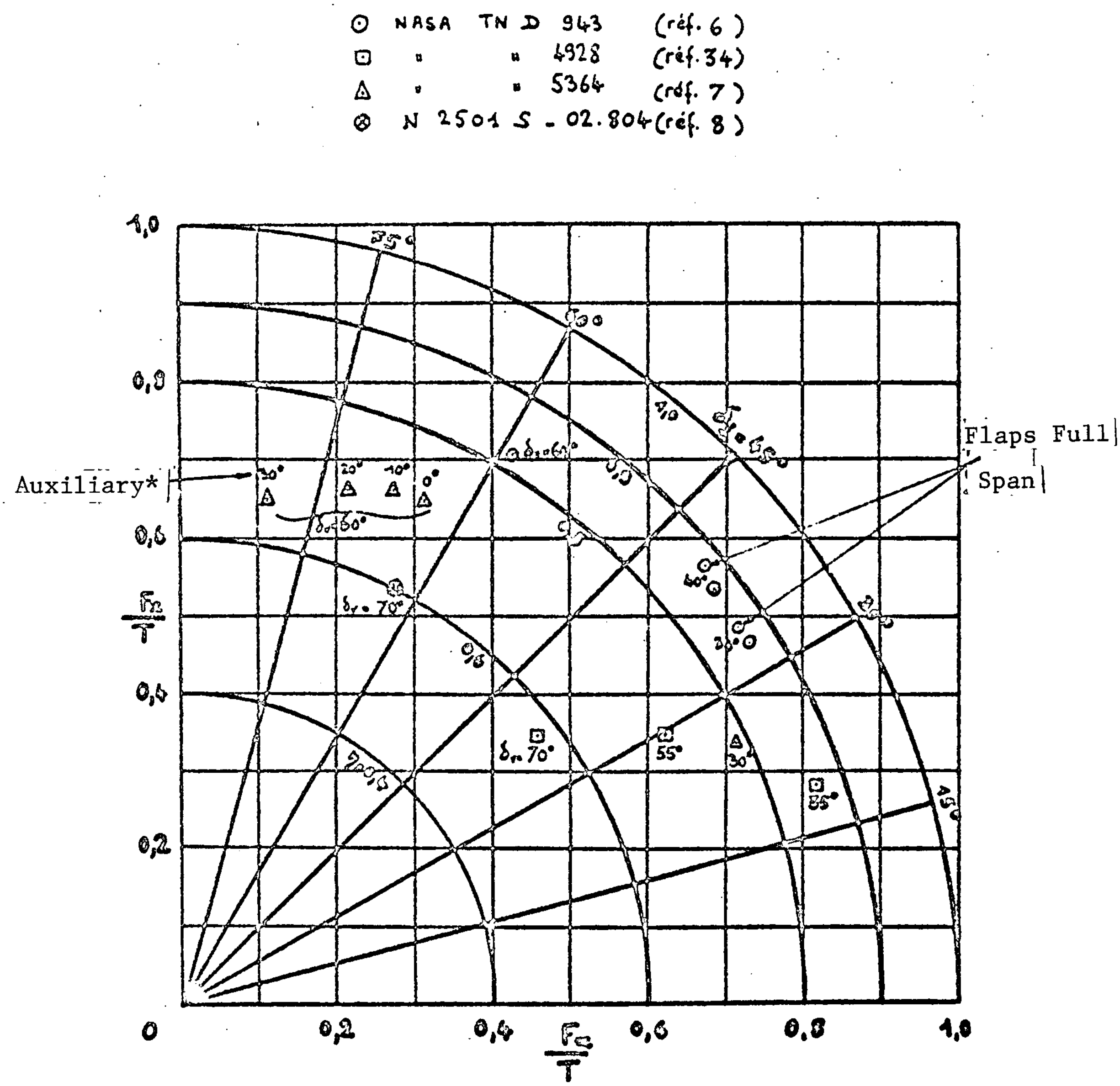


Plate 31

*Translator's Note: Illegible in foreign text.

minimal distance can probably be limited by questions of certification). As we have already shown in § 5.1.2., the distance of the engines can produce a concentration of slip-stream vortices harmful to the directional stability, and to difficulties in longitudinal stability ($1 - d\varepsilon/di < 0$). For the same reason (a distribution of vortices very different from the elliptical one), induced-drag values calculated by classical formulas can be inexact.

More generally, it appears that use of direct blowing can give problems with the slipstream, and there will probably be interest in a study of the effect of a jet on a vortex system.

5.3.4. Attempt at Prediction

Apparently, prediction of characteristics would be more difficult for direct blowing than for indirect blowing. A few remarks might, however, simplify prediction in the first case.

Effect of wing shape /31

The tests of Figure 8 in NACA TN 3898 [21] show that the values of Cz C_z (C_μ) are nearly independent of the plan shape of the wing (straight or swept, $\phi = 30°$, $\lambda \sim 6$).

Effect of number and position of engines

Tests (NACA TN 3898, Figure 9, and NASA 5364) show that C_z (C_μ) is equally insensitive to the disposition of the engines.

Shape of the $C_{z\Gamma}$ (C_μ) curve

Plate 30 shows a large dispersion of the $C_{z\Gamma}$ (C_μ) curves; a mean curve can be assumed to have the form $aC_\mu^{1/2}$, with a being a function of δ_v.

Value of $\theta = \delta_j - \delta_v$

From Plate 31 it is difficult to predict a value of θ. However, $\theta = 0$ will give a first approximation.

The remarks above can obviously give only a very rough prediction. Applying them to the results of Parlett and Shivers [7], one can see in Plate 32 that they give an order-of-magnitude level of ΔC_z for direct blowing.

5.3.5. Partial Conclusions

High lift by direct blowing apparently requires a much simpler installation than does indirect blowing; furthermore, its performance is superior. It must be noted, however, that the flight mechanics problems — equilibrium, stability, engine failure, gas return, etc. — are probably more complicated than for indirect blowing.

Prediction of characteristics requires a certain number of wind-tunnel tests, which can also permit optimization of the engine-flap configuration. /32

A simple calculation can give an order of magnitude of the increase in C_z due to blowing.

VI. CONCLUSIONS /33

We have examined a certain number of problems which are presented to the aerodynamicist concerned with the "low-speed" study of a design. Our purpose was not to give solutions, but to indicate certain areas which seem to us to be insufficiently studied, and for which studies (probably of a basic nature) would be desirable. We also wished to present some methods which are provisionally acceptable. We shall review some of our conclusions below.

Comparison of Prediction with Experiment
Direct Blowing
C_z (C_μ) Curves

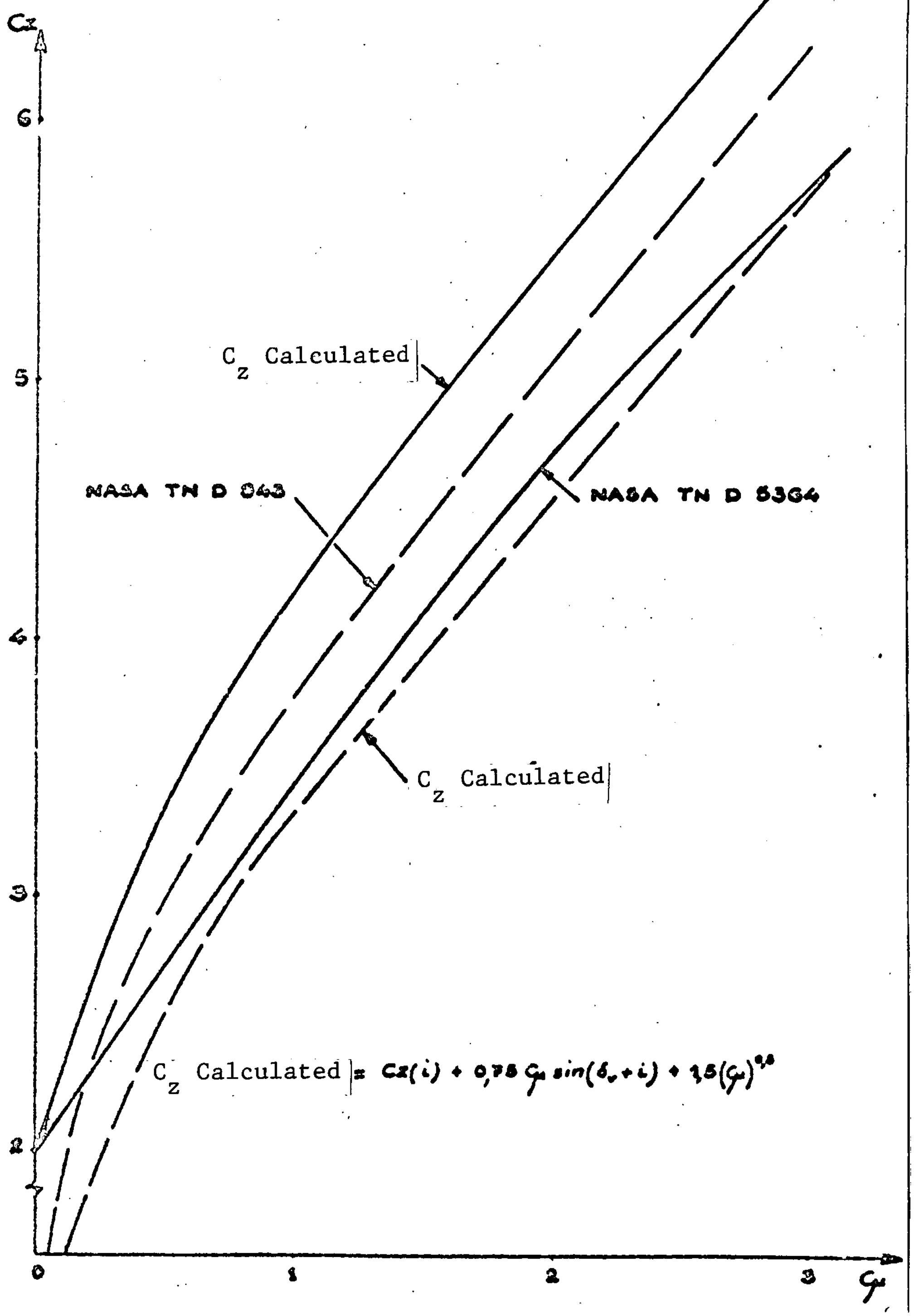


Plate 32

6.1. Wing with "Classical" High Lift Devices

6.1.1. Profile

Known results apply chiefly to NACA profile families. For two examples, at least one of which is a RAE profile with leading- and trailing-edge flaps, it can be established that the predictive methods give an error which can be of the order of 20%, which is probably acceptable for preliminary design.

6.1.2. Complete Wing

It is interesting that very simple methods, such as those shown by Douglas, give a value of $C_{z\ max}$ to a relatively good approximation. Likewise, acceptable values are obtained by McRae's method. Whatever the method used, there is always an uncertainty in the increase in C_z (or the extension in angle of attack of the "linear" part of C_z (i) due to the high-lift device at the leading edge), and also an uncertainty in the shape of the C_z (i) curve not only in the region of $C_{z\ max}$, but also in the pseudo-linear region.

Near $C_{z\ max}$, present methods allow a fairly good approximation of the distribution over the span, at least for wings with small sweep and moderate aspect ratio. Various desirable improvements would include generalization to a wing with any plan shape, in the presence of a fuselage and engine nacelles, and allowing for discontinuities at the leading and trailing edges.

6.2. Wing with Blowing /34

High lift by blowing through the forward engines (sic) is presently contemplated in preference to "mechanical" devices, so that development of predictive methods is particularly important.

6.2.1. Indirect Blowing

As for the wing with conventional high-lift devices, prediction is acceptable for a wing of small sweep and relatively great aspect ratio. Even in two-dimensional flow, however, calculations give imprecise values of the blowing coefficient at re-attachment $C_{\mu R}$. Furthermore, for simultaneous blowing at the leading and trailing edges, not enough experimental results are available to predict the mutual influence of the two types of blowing, or the optimal distribution between the two flows.

6.2.2. Direct Blowing

To our knowledge, there is no predictive method for direct blowing. Up to the present time, only three-dimensional wind-tunnel tests can provide aerodynamic characteristics. It is, however, possible that calculations or tests in a hydro-dynamic cell can serve as a guide , to a certain extent.

6.3. Detachment

At the present state of development, a prediction can be made by knowing only the geometric characteristics; this is generally sufficient for preliminary design. If a more exact prediction is necessary, only a deeper study of the detached flow could yield useful results.

Studies of detachment on profiles and wings are relatively advanced today, /35 since criteria for detachment in two and three dimensions give at least a partial idea of the flow. Nevertheless, even for the smooth wing, there is still no practical and general method of calculation for a wing with detachment. To be truly useful, this method would have to be applicable to a wing with high-lift devices.

6.4. General Conclusions

As we have determined, prediction of the characteristics ΔC_z and $C_{z\ max}$ at low velocities is now possible at the preliminary-design stage by methods which are generally empirical. Improvement in the precision of these methods can result only from a better understanding of flows over high-lift wings — from fundamental research, especially on the following subjects:

Interaction of boundary layers and slipstreams

In practice, because of the presence of slipstreams from the various flaps, the boundary layers are different from those of a smooth wing (Plate 6). It is probably the same for the detachment conditions.

Jet (parallel to $\vec{V}_\infty$) at the surface of a wall (indirect blowing)

This problem has often been approached in particular cases — plane plate, "Coanda effect," etc. There does not seem to be a general method (which considers air entrainment) which allows, for example, the study of the interaction of a leading-edge jet on the trailing-edge flow, with flap blowing.

Action of a jet on a wing with flaps (direct blowing) /36

If we replace a jet by a system of singularities — vortices, doublets, and sinks (these latter singularities allow consideration of air entrainment) — it is possible, at least in principle, to make a calculation for the wing-jet combination, the wing being replaced by an equivalent vortex system.

Action of a jet on a free vortex system

Lateral blowing is a particularly striking example of the action of a jet (oblique or perpendicular to $\vec{V}_\infty$) on a detached zone.

One other example is that of the action of an engine jet on the turbulent slipstream coming from the wing, an action which must condition the deflection, the induced drag, etc. This problem has been studied in the hydrodynamic tunnel at ONERA, chiefly for the action of an engine jet on the marginal vortex coming from a discontinuity in a flap.

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